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Vegetation classification for northwestern Arctic Alaska using an EcoVeg approach: tussock tundra and low and tall willow groups and alliances

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Abstract

Aims: The USNVC is the standard for vegetation classification in the US and is part of the broader IVC. Recent work on the USNVC in Alaska established macrogroups, groups and alliances. Here we incorporate tussock tundra and low and tall willow (*Salix*) groups and alliances for northwestern Arctic Alaska into the IVC and USNVC classification. **Study Area:** The study area encompasses the Seward Peninsula, the western Brooks Range, and the northwestern foothills and Arctic coastal plain of Alaska. **Methods:** We used data from 2,087 relevé plots collected between 1992 and 2019 from northwestern Arctic Alaska to prepare a draft association classification using cluster analysis, ordination, and sorted tables. The draft classification was subject to peer review and subsequently refined. We fit the tussock tundra and low and tall willow associations into the USNVC using NMDS and GAMs to evaluate the patterns of environmental gradients against the ordination axis scores. **Results:** We identified eight tussock tundra and 37 low and tall willow associations. The associations fit in two classes, two subclasses, two formations, two divisions, three macrogroups, four groups, and 13 alliances. A description of the alliances, and a field guide to the northwestern Arctic Alaska tussock tundra and low and tall willow associations, including a dichotomous key and descriptions, is provided. **Conclusions:** Many of the tussock tundra and low and tall willow associations fit seamlessly within the USNVC, while some alliances had yet to be defined, and we have proposed new alliances here. In still other cases, we proposed a new group and recommend broadening the concept of an existing group using a data-driven approach. Since not all available data from Arctic Alaska were used in this study, we suggest continuing with a more comprehensive analysis to fulfill the gap at the alliance and association levels for Arctic Alaska.

Taxonomic reference: USDA NRCS (2021) for vascular plants, bryophytes, and lichens.

Syntaxonomic reference: USNVC (2019).

Abbreviations: AVA-AK = Alaska Arctic Vegetation Archive; AVPD = Alaska Vegetation Plots Database; BCP = Beaufort Coastal Plain; CAVM = Circumpolar Arctic Vegetation Map; CBVM = Circumboreal vegetation map; EC = Electrical conductivity; ELD = ELS Legacy Database; ELS = Ecological Land Survey; GAM = Generalized additive model; IVC = International vegetation classification; LPI = line-point intercept; NMDS = Non-metric multidimensional scaling; PAM = Partitioning Around Medoids; PESC = Proportionate ericaceous shrub cover; SM = Supplementary material; US = United States of America; USNVC = U.S. National Vegetation Classification.

Keywords

alliance, association, *Eriophorum vaginatum*, group, IVC, *Salix*, USNVC

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Introduction

Vegetation classifications have a deep and rich history in the many phytosociological studies of Europe (Braun-Blanquet and Jenny 1926; Pignatti 1994, 1995; Pignatti et al. 1995; Chytrý 2000; Mucina et al. 2016; Chytrý et al. 2020). According to Peet and Roberts (2013), the goal of vegetation classifications is "to identify, describe and interrelate relatively discrete, homogeneous and recurrent assemblages of co-occurring plant species." Vegetation classifications are a fundamental component of ecological studies as they provide a benchmark for monitoring landscape change (Ravolainen et al. 2020), developing state and transition models (Bestelmeyer et al. 2017), preparing vegetation and wildlife habitat maps (Walton et al. 2013), and developing statistically rigorous stratified study designs (Austin and Heyligers 1989), among other uses. Given the rapid rates of landscape change across the globe in recent decades (Song et al. 2018), the need for vegetation classifications is acute. This is especially so for the Arctic, where climate change is occurring at an accelerated rate due to Arctic amplification (Serreze and Barry 2011; Thoman et al. 2020).

The International Vegetation Classification (IVC) provides a "comprehensive multi-level structure to describe and classify the world's vegetation and ecosystems" (Mucina et al. 2016; NatureServe 2021) and is based on the EcoVeg approach (Faber-Langendoen et al. 2014). EcoVeg is a physiognomic-floristic-ecological classification approach that applies to existing vegetation (natural and cultural), and is based on a set of vegetation criteria, including physiognomy and floristic composition, in conjunction with ecological characteristics including topoedaphic factors, disturbance, bioclimate, and biogeography. NatureServe manages the data content for the IVC, working in collaboration with international partners and the U.S. National Vegetation Classification (USNVC).

The USNVC is the standard for vegetation classification and mapping for state and federal agencies in the United States of America (US) and is based on the EcoVeg approach (FGDC 2008; Faber-Langendoen et al. 2009; Franklin et al. 2012; MacKenzie et al. 2018). The USNVC is hierarchical and includes eight levels (from highest to lowest): class, subclass, formation (Faber-Langendoen et al. 2016), division, macrogroup, group, alliance, and association. At the class level, vegetation is classified based on broad combinations of dominant growth forms (e.g., mesomorphic shrubs and herbs vs xeromorphic shrubs and herbs) and regional climate (e.g., ecoregions). At the alliance and association levels, vegetation is defined by unique assemblages of plant species that occur predictably across the landscape; these levels are characterized by diagnostic species, usually from multiple growth forms (e.g., tall shrub) and by vegetation-landform-soil relationships and disturbance regimes (e.g., riverine sedimentation; Willner 2020).

The USNVC is a work in progress, and the process of developing the classification is highly collaborative. For instance, contributions to the USNVC require peer-review (Jennings et al. 2009) of draft classifications, and working groups periodically meet to make progress towards developing the classification. To this end, a USNVC workshop was conducted November 7–9, 2017 in Anchorage, Alaska to review existing macrogroups, groups, and alliances for the three biomes in Alaska–Arctic & Alpine, Boreal, and Coastal Pacific (Nowacki et al. 2001). The results of the workshop were a series of revisions based on expert knowledge, maps, and available publications as detailed in Faber-Langendoen et al. (2020).

Beginning in 2018, we began compiling and harmonizing historical Ecological Land Survey (ELS) datasets from across Alaska into a centralized database, the ELS Legacy Database (ELD), for use in ecological land classification and mapping. The ELD contains data collected by ABR, Inc.–Environmental Research and Services between 1992 to 2019 on vegetation composition and structure, and the associated soil, physiographic setting, hydrology, and site chemistry. The ELD contains 6,986 relevé plots sampled across 31 field studies that were sampled using stratified study designs and standardized methods (Suppl. material 1). The primary purpose of the ELD is to contribute field data to circumarctic, circumboreal, and regional vegetation classification and mapping efforts. We recognize there are other statewide- and Alaska Arctic-wide vegetation databases available like the Alaska Arctic Vegetation Archive (AVA-AK, Walker et al. 2016a) and the Alaska Vegetation Plots Database (AVPD, ACCS 2019) which, combined with the ELD, would provide a more comprehensive view of Arctic vegetation in Alaska. However, incorporating these datasets was beyond the scope of this study.

The ELS approach is based on the principle that local-scale features (e.g., geomorphic units, vegetation) are nested hierarchically within landscape- and regional-scale components (e.g., physiography and climate; Figure 1). The ELS and EcoVeg approaches are similar in many aspects and share the fundamental concept that vegetation classifications must be developed within an ecological context to be relevant across spatial and temporal scales.

We used relevé plot data from the ELD to prepare a draft plant association (hereafter "association," following USNVC terminology, and reflecting its floristic-ecological concept) classification for low and tall willow and tussock tundra vegetation in northwestern Arctic Alaska using an EcoVeg approach. The draft classification underwent informal peer review by several local and regional experts (see Acknowledgments), and the classification was then revised based on feedback from the reviewers. We then developed draft keys to the tussock tundra and low and tall willow (*Salix*) associations and revised them after further peer review and field testing. Finally, we evaluated these associations with respect to the current IVC and USNVC classifications to the alliance level using ordination analysis and Generalized Additive Models (GAMs).

Here we describe the methods used to prepare the ELD northwestern Alaskan Arctic association classification,

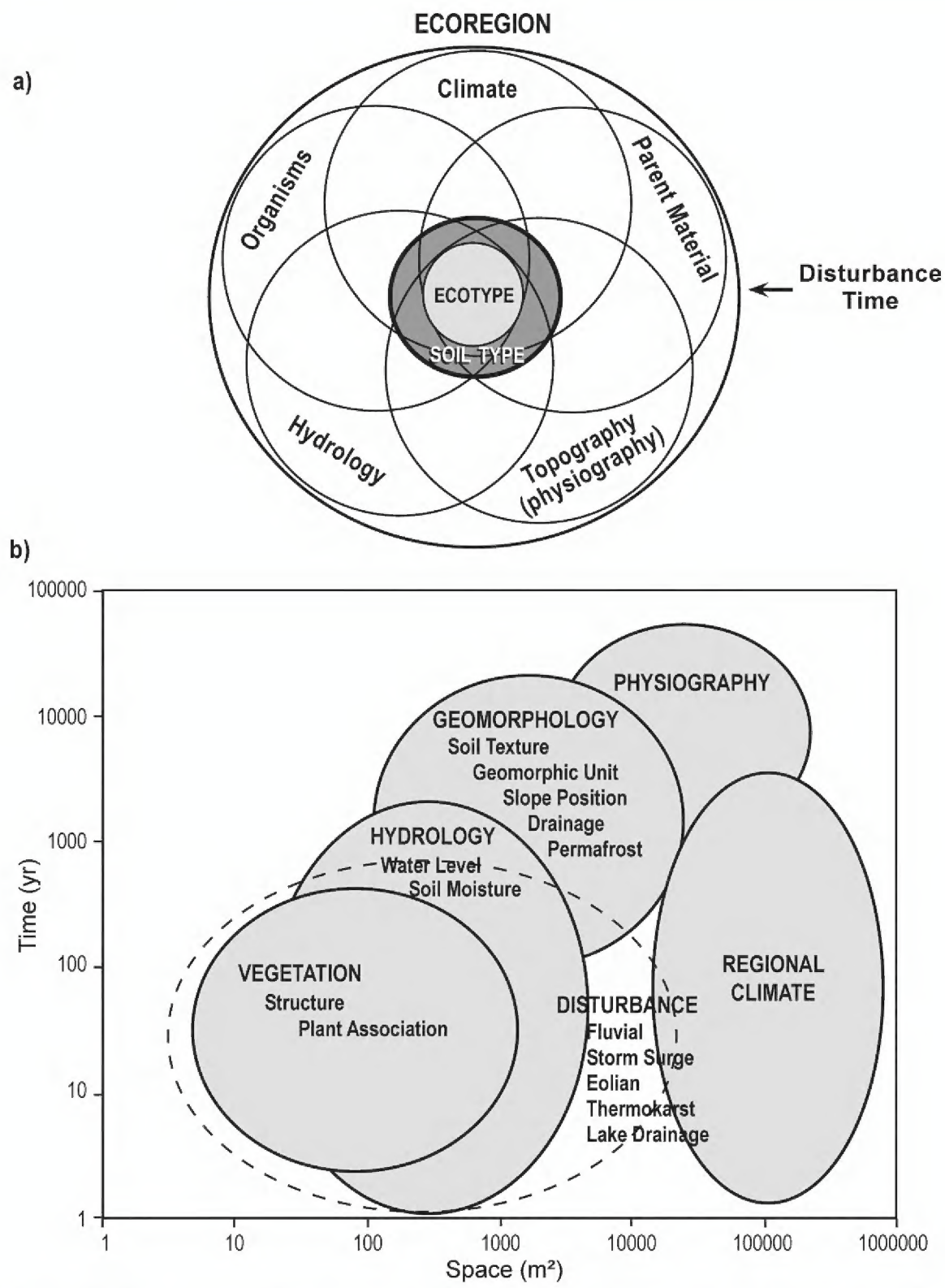


Figure 1. Interaction of interrelated state factors that control the structure and function of ecosystems (**a**) and the scale at which they operate (**b**).

incorporate the tussock tundra and low and tall willow associations into the IVC and USNVC classifications, and provide recommendations for revisions to the classification of Faber-Langendoen et al. (2020). In addition, we provide field guides and summaries for the tussock tundra and low and tall willow alliances and associations, including dichotomous keys, written descriptions, constancy/cover tables, photographs, maps, and environmental data summaries.

Study area

The study area encompasses northwestern Arctic Alaska, including the northern Seward Peninsula, the western Brooks Range, and the northwestern foothills and coastal plain (Figure 2), and spans three Circumpolar Arctic Bioclimate Subzones (E, D, and C; CAVM Team 2003). The foothills and coastal plain subzones consist of broad areas of Quaternary alluvial-marine, eolian sand, and glacio-marine deposits (Carter 1981; Williams 1983; Rawlinson 1986). The foothills consist predominantly of colluvial material capped by thick loess, and, east of the Colville River, glacial deposits (Hubbard 2016). The Brooks Range is the most northerly extension of the Rocky Mountain Cordillera and is characterized by a diversity of bedrock geology types, including granitic intrusive and sedimentary rocks, and Quaternary surficial deposits in valley bottoms. The Seward Peninsula is in western Arctic Alaska and is mountainous in the central and southern portions, with a broad coastal plain to the north.

North of the Brooks Range, in Bioclimate Subzones C and D, the climate is characterized by very cold mean annual temperatures. Three long-term weather stations (Menne et al. 2012a, 2012b) are in this part of the study area at Kuparuk, Utqiaġvik, and Wainwright. The 30-year average summer high temperature at these stations range from 6.9°C at Utqiaġvik to 11.0°C at Kuparuk, while the average low temperature in winter ranges between -23.1°C at Wainwright and -25.9°C at Kuparuk. Precipitation north of the Brooks Range is low, with mean total yearly precipitation values ranging from 112 mm at Wainwright to 137 mm at Utqiaġvik. More than 70% of the precipitation falls between April and September, most of this in the form

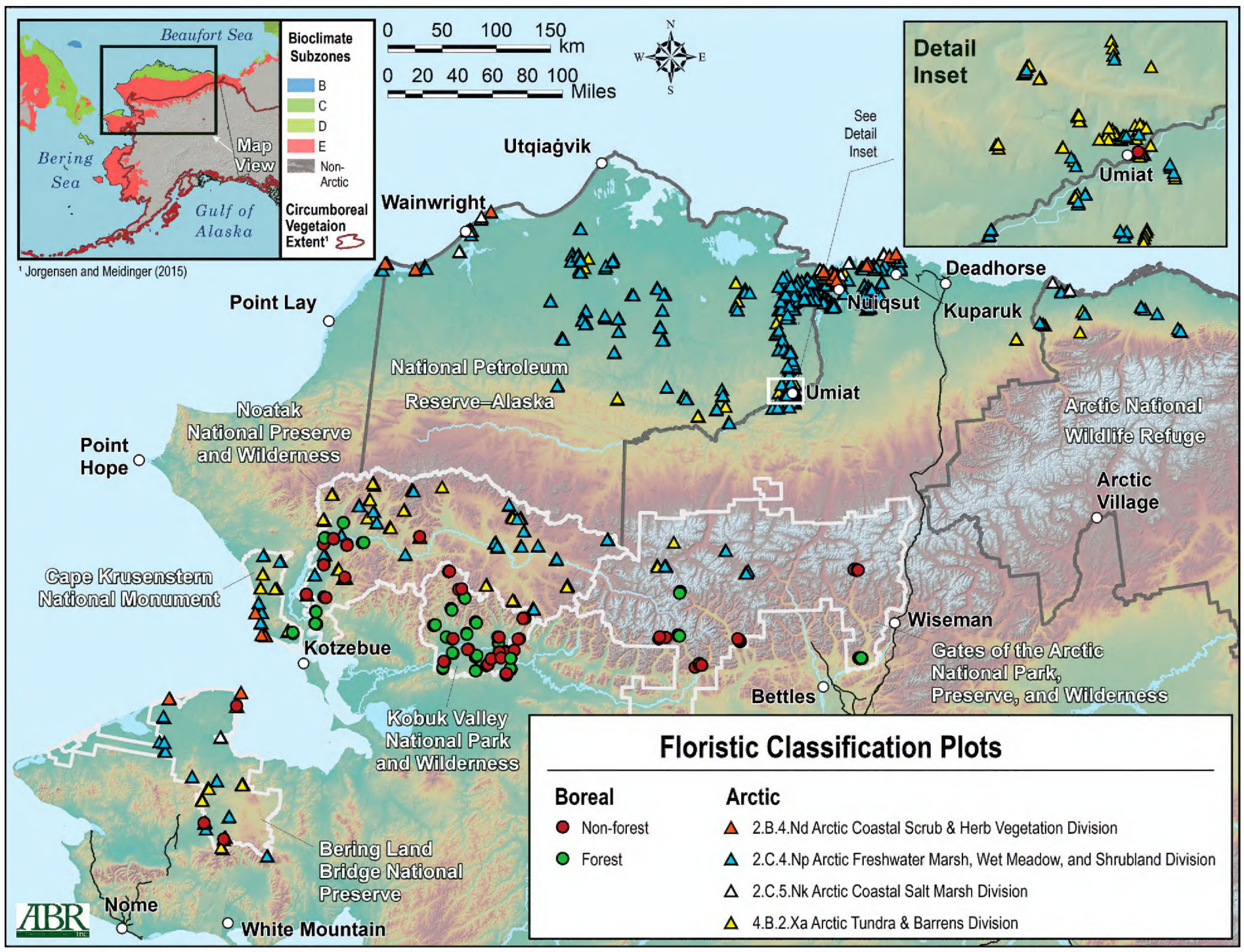


Figure 2. Study area map showing the locations, ecoregions, and USNVC divisions of the plots used in the Ecological Land Survey Legacy Database (ELD) Arctic association classification, Alaska. Inset overview map shows the Arctic Bioclimatic Subzones from the CAVM Team (2003).

of snow, except for the warmest months, July and August, during which precipitation typically falls as rain.

The Brooks Range, its southern foothills, and Seward Peninsula lie in Bioclimate Subzone E, the warmest subzone. Five long-term stations are in this climate region; three coastal stations at Kotzebue, Nome, and White Mountain; and two inland stations at Bettles and Wiseman (Figure 2). Climatic conditions in this region are generally warmer than the tundra north of the Brooks Range, and there is a pronounced coast-inland climate gradient. There is greater seasonality in this portion of the study area with colder overall winter temperatures, especially inland, and warmer summer temperatures. Average yearly minimum temperatures range from -11.0°C to -15.6°C at the coastal stations and are just under -25°C at the inland stations. Summer temperatures at the western and coastal stations average between 13.5°C at Nome to 15.6°C at White Mountain and are above 19°C at the inland stations. Annual precipitation is variable, with Wiseman, Bettles, and Nome all receiving more than 400 mm of precipitation in a normal year. Kotzebue has a lower mean total precipitation of 289 mm.

Most of the study area lies in the zone of continuous permafrost (> 90% of landscape; Brown et al. 2001). Despite the dry climate, surface soils north of the Brooks Range generally remain saturated throughout the thaw season due to shallow (< 50 cm) permafrost, which acts as an aquitard, and very low evapotranspiration. In the Brooks Range and its southern foothills, the rugged topography promotes better soil drainage on slopes and in areas dominated by bedrock and coarse-textured soils (e.g., glacial deposits).

The vegetation is Arctic tundra, characterized primarily by dwarf and prostrate shrubs and graminoids. In the Brooks Range and across the mountainous portions of the Seward Peninsula, an arctic alpine zone occurs above approximately 400 m a.s.l. elevation. Northern extensions of the boreal forest, dominated primarily by white spruce (*Picea glauca)* and balsam poplar (*Populus balsamifera*), occur in the southernmost portion of the study area.

Methods

Field methods

We used existing data from the ELD that were collected using standardized ELS field protocols across a variety of studies over an approximately 30-year period. The field methods met the criteria described in Walker et al. (2018) for maxi-

mizing the value of Arctic vegetation plot surveys. The field protocols used are briefly described here; for a detailed description of the field methods see Wells et al. (2016).

Field surveys were designed to balance consistency (i.e., a core set of protocols) with flexibility (i.e., the addition of project-specific protocols) so that the methods could be used across a variety of field projects. Transect locations were selected using a gradient-directed sampling scheme (Austin and Heyligers 1989) to sample the range of ecological conditions present across each study area, and to provide the spatially related data needed to interpret ecosystem development. Transects were typically 1.5–2.0 km long and were stratified within the major geomorphic units and vegetation types, and across the soil moisture and salinity gradients present within each study area.

During fieldwork, we established plots subjectively along each transect to sample both (1) the range of environmental settings and gradients present; and (2) the distinct photo-signatures evident in satellite or aerial imagery. Standard field plots were circular in shape with an approximate radius of 10 m and were situated within a homogeneous vegetation type or photo-signature. At field plots, we recorded quantitative and categorical data on plot location, geomorphology, landscape position, macro- and microtopography, soil stratigraphy (USDA NRCS 2007), hydrology (e.g., water table depth, soil drainage), soil and water chemistry (e.g., pH, electrical conductivity [EC]), and soil thaw depth. Vascular plant, bryophyte, and lichen species composition data and vegetation structure data were also recorded at each plot. Identification of bryophytes and lichens to species-level during field sampling was generally limited to readily identified species. Nonvascular species that we could not identify with confidence in the field were collected and sent to specialists for identification. Species composition and vegetation structure data were recorded as percent foliar cover by species and growth form (e.g., dwarf shrub), respectively. For most projects foliar cover was recorded using the semi-quantitative ocular (i.e., visual) estimates method (Elzinga et al. 1998). However, for some projects the line-point intercept (LPI) method was used to quantitatively measure canopy hits by species, in which case the LPI data were normalized to foliar cover by species and growth form for analysis purposes (see below, Plot Data). Landscape, ground cover, and soil photographs were taken at all field plots. Plant voucher specimens were collected and deposited at local herbaria for long-term curation. Depending on the objectives of the study, some plots were permanently monumented, but most were not.

Northwestern Arctic Alaska association classification

Plot data

Data from 6,986 relevé plots sampled across 31 individual field studies from across broad areas of Alaska, between 1992 and 2019, were compiled into the ELD (Suppl. material 1). Of the field plots in the ELD, we used a subset located in the Arctic to prepare the association classification presented here. Initially, we selected all 2,255 plots located on the Seward Peninsula and Chukchi Sea coast, in the western Brooks Range, and all areas north of the Brooks Range that had complete plant species composition data (Figure 2). These plots were from five projects spanning 27 years (Table 1).

Table 1. Datasets used in the Ecological Land Survey Legacy Database (ELD) Arctic plant association classification, Alaska.

Project	Client	Timeframe	Citation	Number of Plots
Integrated Terrain Unit (ITU) mapping	ConocoPhillips Alaska, Inc.	1992–2018	Wells et al. (2020)	842
Integrated Terrain Unit (ITU) mapping	Hilcorp (formerly BP Exploration (Alaska) Inc.)	2008	Roth et al. (2009)	26
Onshore Environmental Studies program	Shell Oil Company	2011–2012	Macander et al. (2013)	492
North Slope of the Arctic National Wildlife Refuge Land Cover mapping	U.S. Fish and Wildlife Service	2019	Macander et al. (2020)	35
Ecological Land Survey (ELS) and Land Cover mapping for the Arctic Network	U.S. National Park Service	2002–2008	Jorgenson et al. (2009)	860
Total				**2,255**

After selecting the initial subset of plots, we assigned plots to an ecoregion, either Boreal or Arctic, using an iterative process. Our goal for assigning ecoregions to plots was to distinguish associations that represent boreal extensions into the Arctic versus true Arctic associations. We assigned all forested plots and all plots located on transects along which a forested plot was sampled to Boreal. All remaining plots outside of the Circumpolar Arctic Vegetation Map (CAVM) extent were assigned to Boreal. All other plots were provisionally assigned to the Arctic ecoregion pending further review and analysis. We then compared the plot ecoregion assignments to the extent of the Alaska-Yukon Region of the Circumboreal Vegetation Map (CBVM; Jorgensen and Meidinger 2015). We manually reviewed plots assigned to the Arctic ecoregion that occurred within the CBVM extent and made changes to ecoregion assignments on a plot by plot basis. During this phase, plots dominated or codominated by characteristically boreal taxa (e.g., *Carex rostrata*) were assigned to the boreal ecoregion. In subsequent analyses, we included all Arctic and Boreal plots, except for 129 forested plots, and used the results to refine the plot ecoregion assignments. We withheld forested plots (i.e., plots with ≥ 10% tree cover) from this analysis because the focus of this study was on non-forested Arctic tundra vegetation. The final dataset for use in the Arctic

association classification analyses consisted of 2,087 plots, of which 1,825 were assigned to the Arctic ecoregion and 262 were assigned to boreal.

Foliar cover vs. canopy cover

Foliar cover is the percentage of ground covered by the vertical portion of plants, excluding small openings in a canopy or intraspecific overlap (Jennings et al. 2009). Foliar cover differs from canopy cover, the standard for USNVC, in that canopy cover is the percentage of the ground covered by a vertical projection downward of the outermost perimeter of the natural spread of foliage of plants. We selected foliar cover because it can be estimated using the ocular estimate method and calculated from line-point intercept data, a commonly used method for quantitively measuring vegetation cover, while canopy cover cannot be calculated as readily from the later. Choosing foliar cover as our cover metric allowed us to use a wider variety of available plot data, including from projects that used the LPI method. In general, foliar cover is lower than canopy cover for the same plant because foliar cover discounts canopy gaps. Throughout the remainder of this manuscript, when we use the word "cover" we are referring to foliar cover.

Draft classification

We used ordination, cluster, and sorted-table analyses to prepare a draft association classification for low and tall willow and tussock tundra vegetation. To begin, for plots sampled using the LPI method we calculated foliar cover for each species and growth form as the number of points at which each species or growth form was hit, divided by the total number of points, times 100. This ensured that all plots were standardized to foliar cover. Next, we standardized taxonomy, and performed several data transformations which are described below.

Taxonomic considerations

In the field, plant taxonomic nomenclature was based on Viereck and Little (2007) for trees and shrubs, Skinner et al. (2012) for grasses, and Hultén (1968) for all other vascular taxa. We selected these taxonomic references for field work because they provide dichotomous keys for field identification purposes. Nomenclature for bryophytes and lichens followed the USDA NRCS (2021). For data analysis we standardized plant nomenclature following USDA NRCS (2021), the current taxonomic standard for the USNVC. Of the 1,031 taxa in the dataset, 26 were not recognized by USDA NRCS (2021) (Table 2). Each of the unrecognized taxa occurred in less than 4% of the plots in the dataset. For these 26 taxa the original taxonomic names assigned in the field were used for data analysis.

The foliar cover data were then harmonized in several ways for the purpose of ordination and cluster analysis. First, vascular plant subspecies and varieties were aggregated to the species level. Second, nonvascular species were aggregated to genus level, and only nonvascular genera were included in the floristic analysis. Both aggregations were required due to differences in taxonomic resolution between the vascular and nonvascular plant datasets. Third, all vascular species with cover < 1% and nonvascular genera with cover < 5% were excluded from the analysis. We excluded species with cover values below these thresholds because the purpose of the cluster and ordination analyses was to distinguish preliminary groupings of plots with similar dominant or co-dominant species. We recognize the taxonomic diversity in the Arctic bryophyte and lichen flora and appreciate that individual species within a single genus can have different ecological requirements. However, the field protocols for recording ocular cover estimates of bryophytes and lichens differed between projects included in this dataset. For most projects we recorded cover estimates for an exhaustive list of bryophytes and lichens, while for some projects only dominant (≥ 5% cover) bryophytes and lichens were recorded. Therefore, for analysis purposes we standardized the bryophyte and lichen data across datasets by applying the genus aggregation and < 5% cover criteria described above. Fourth, unknown species codes and vascular taxa identified to genus level only were excluded from the analysis.

Data transformations

Following the application of the taxonomic standardizations described above we performed several additional data transformations. First, plots with < 5% live cover of vascular and nonvascular species, such as plots representing waterbodies and barrens, were withheld from the analysis. Additionally, any plots that had less than two taxa remaining after the above transformations were withheld from the analysis. Lastly, the percent cover data were natural log transformed as follows: natural log(percent cover) + 0.1. The addition of 0.1 was required because the natural log of 1 is zero. Adding 0.1 sets cover values of 1 to 0.1 for use in the analysis. The natural log transformation was performed because it down-weights dominant species in the analysis. The final floristic analysis dataset had both raw and transformed cover values. The raw and transformed cover values were both used in subsequent analyses and the results were assessed to determine which cover values provided the best balance between statistical significance and floristic and ecological relevance.

In addition to the transformed vegetation dataset, we also used a partially transformed vegetation dataset for the purpose of sorted table and constancy/cover analysis. The partially transformed vegetation dataset was like the transformed dataset except that all taxa were included regardless of cover, nonvascular taxa were included at the species level, and the cover values were not log-transformed. This is because the primary purpose of these two analyses was to identify characteristic species–those plant species that are always present (sometimes at very low abundance) and are indicative of unique site characteristics (e.g., soil pH), and that differentiate the preliminary groupings of plots from the ordination and cluster analysis into unique associations.

Cluster analysis and ordination

After transformation, the data were ingested into R (R Core Team 2020). We split the dataset by vegetation physiognomy class (e.g., low and tall willow), and we analyzed plots separately for each class. Vegetation was clustered using the fixed clustering algorithm Partitioning Around Medoids (PAM; Kaufman and Rousseeuw 1990), and a Bray/Curtis dissimilarity matrix (Bray and Curtis 1957) was used to develop preliminary groupings of similar vegetation. We used Partana analysis (Roberts 2020) to assess the strength of each cluster and to determine which clusters were most floristically like one another, based on the within to between cluster similarity. We applied non-metric multidimensional scaling (NMDS; Shepard 1962a, 1962b; Kruskal 1964a, 1964b) to the dissimilarity matrix to chart the plots in species space, assess patterns of dispersion, and identify outliers. We used the ordination plotting functions provided in the "vegan" (Oksanen et al. 2019), "labdsv" (Roberts 2019), and "rgl" (Adler et al. 2019) R libraries to plot the NMDS ordinations as 3-dimensional, dynamic plots that could be viewed from multiple perspectives. Outlier plots were flagged in the database and withheld from subsequent analysis. Additionally, we used Generalized Additive Models (GAMs) to visualize environmental gradients across the ordinations of vegetation. Ideally, we would have included in our analysis all available relevé data for Arctic Alaska (e.g., AVA-AK). However, such an effort was beyond the scope of this study. To address this shortcoming, while preparing the classifications, we referenced existing association classifications for Alaska (e.g., Cooper 1986; Boggs et al. 2014, 2018; Walker et al. 2016b) to ensure that our classification dovetailed with existing literature.

Peer review

Per the USNVC standard, we initiated a peer-review process by sending the list of tussock tundra and low and tall willow associations and all information necessary to review the classification (e.g., constancy/cover tables), to local and regional experts (see Acknowledgments). To revise the classification, we first reviewed constancy/cover and environmental data summary tables by association to tighten the range in cover values for dominant, co-dominant, and characteristic species, and the range in environmental characteristics by association. After evaluating the environmental summary and constancy/cover tables, and adjusting the class membership of plots accordingly, we then prepared the revised list of associations. We assigned classes with a sample size ≥ 10 a provisional association status, classes with a sample size 4–9 a preliminary association status, and classes with a sample < 4 a plant community type status.

Next, we further refined the draft classification by developing draft association keys. In the process of developing the keys, additional minor revisions were made to the tussock tundra and low and tall willow associations. Our purpose for selecting this subset of associations, rather than all northwestern Arctic Alaska associations, was to treat this as a pilot study for a larger effort of refining the entire ELD Arctic Alaska classification and fitting it into the USNVC.

We fit the tussock tundra and low and tall willow associations into the USNVC classification for Alaska (Faber-Langendoen et al. 2020) by first assigning all Arctic plots to a USNVC division based on physiography, soil moisture, and hydrology, and then performed a series of NMDS ordination analyses for the tussock tundra and low and tall willows plots within each division to iteratively assign plots into macrogroups, groups, and alliances. Specifically, we used NMDS to assess the distribution of plots based on species composition against the axis scores to determine if the distribution of each deviated significantly from random (Roberts 2019). We then fit GAMs to the ordination axis scores for continuous environmental attributes (e.g., soil pH), and plotted the smoothed surfaces over the NMDS (Oksanen et al. 2019). Throughout this process we used silhouette analysis to evaluate the within to between cluster similarity at the various levels of the USNVC hierarchy.

We used bar charts to evaluate the range of environmental attributes by alliance, and indicator species analysis (Dufrene and Legendre 1997; Roberts 2019) to evaluate the fidelity and relative abundance of species in each alliance. Lastly, we prepared keys to the divisions, macrogroups, groups, alliances, and associations for the tussock tundra and low and tall willow associations, and prepared descriptions of preliminary (n = 4–9) and provisional ($n \geq 10$) associations, including constancy/cover tables, environmental data summaries, and representative photographs.

USNVC nomenclature and coding

Throughout this document we use official USNVC titles and codes when referring to the various levels of the classification, including using the ampersand (&) in place of the word "and." The first time a USNVC title is discussed we spell out the title, including the level (e.g., Division), followed by the code in parentheses (e.g., Arctic Tundra & Barrens Division (4.B.2.Xa)), and subsequently use only the title (e.g., Arctic Tundra & Barrens). Throughout the manuscript we propose changes to some group titles and introduce one proposed new group and several proposed alliances. When proposing name changes, we use the official title throughout the manuscript and only mention the proposed name change once when it is first proposed. We use the following convention when referring to proposed new groups and alliances: proposed new titles are followed by "Proposed" (e.g., Arctic Minerotrophic Wet Low Shrublands Alliance Proposed) and proposed new codes are followed by "p" (e.g., A4367p).

Association nomenclature

Association titles follow a hierarchical nomenclature beginning with the dominant species in the uppermost canopy layer and ending with the characteristic species

in the lowest canopy layer. In shrubland vegetation, this follows the general pattern of shrub/herbaceous (e.g., *Salix alaxensis/Equisetum arvense*). En-dashes were used between co-dominant species within the same canopy layer, and forward slashes were used to separate canopy layers (e.g., *Betula nana–Salix pulchra/Eriophorum vaginatum*). For herbaceous associations with a subdominant shrub species, the herbaceous species was listed first, followed by the shrub species (e.g., *Eriophorum vaginatum/Dryas integrifolia*). The association classification conforms to the association level of the USNVC Standard (FGDC 2008; USNVC 2019).

Results

Divisions

We assigned the Arctic plots to four USNVC divisions: Arctic Coastal Scrub & Herb Vegetation (2.B.4.Nd), Arctic Coastal Salt Marsh (2.C.5.Nk), Arctic & Boreal Freshwater Marsh, Wet Meadow & Shrubland (2.C.4.Np), and Arctic Tundra & Barrens (4.B.2.Xa; Figure 2). The NMDS analysis indicated that the four divisions were well differentiated ($p < 0.001$) based on plant species composition (Figure 3, Suppl. material 2A). The greatest overlap was between plots in Arctic Coastal Scrub & Herb Vegetation and Arctic Coastal Salt Marsh, which represent salt-water influenced areas on dunes and sandy/rocky beaches, and tidal flats, respectively. NMDS axis 2 represents a soil moisture gradient as illustrated in Figure 3A which displays the results of a GAM which predicts water table depth as a function of the ordination axis scores. Drier soils (i.e., deeper water tables) are predicted lower on axis 2 corresponding to Arctic Tundra and Barrens, while wetter soils (i.e., shallower water tables) are predicted on the upper end of axis 2 corresponding to Arctic & Boreal Freshwater Marsh, Wet Meadow & Shrubland. Figure 3B reveals a gradient in soil electrical conductivity (EC) along NMDS axis 3. EC is strongly influenced by the concentration of dissolved solids in a liquid, such as the salts in seawater. The results reflect this, with the highest values predicted along the upper section of axis 3 corresponding to plots in Arctic Coastal Scrub & Herb Vegetation and Arctic Coastal Salt Marsh. The above results illustrate some of the important broad-scale environmental gradients, including physiography and hydrology, that differentiate Arctic vegetation at the division level of the USNVC.

Macrogroups

The tussock tundra and low and tall willow associations fall within the USNVC divisions Arctic & Boreal Freshwater Marsh, Wet Meadow & Shrubland and Arctic Tundra & Barrens. The NMDS and silhouette analyses of all plots in Arctic Tundra & Barrens indicated two broad plot groupings ($p < 0.001$) optimized the ratio of within to between cluster similarity as measured by the average silhouette width (ASW) (Figure 4A, Suppl. material 2B). The two plot groupings correspond to the USNVC macrogroups Arctic Dry-Moist Tundra (M173) and Arctic Scree, Rock & Cliff Barrens (M175). GAMs of surface organic (Figure 4B) and active layer (Figure 4C) thickness, and soil pH (Figure 4D) explained 38%, 51%, and 65% of the deviance in the distribution of plots across the NMDS

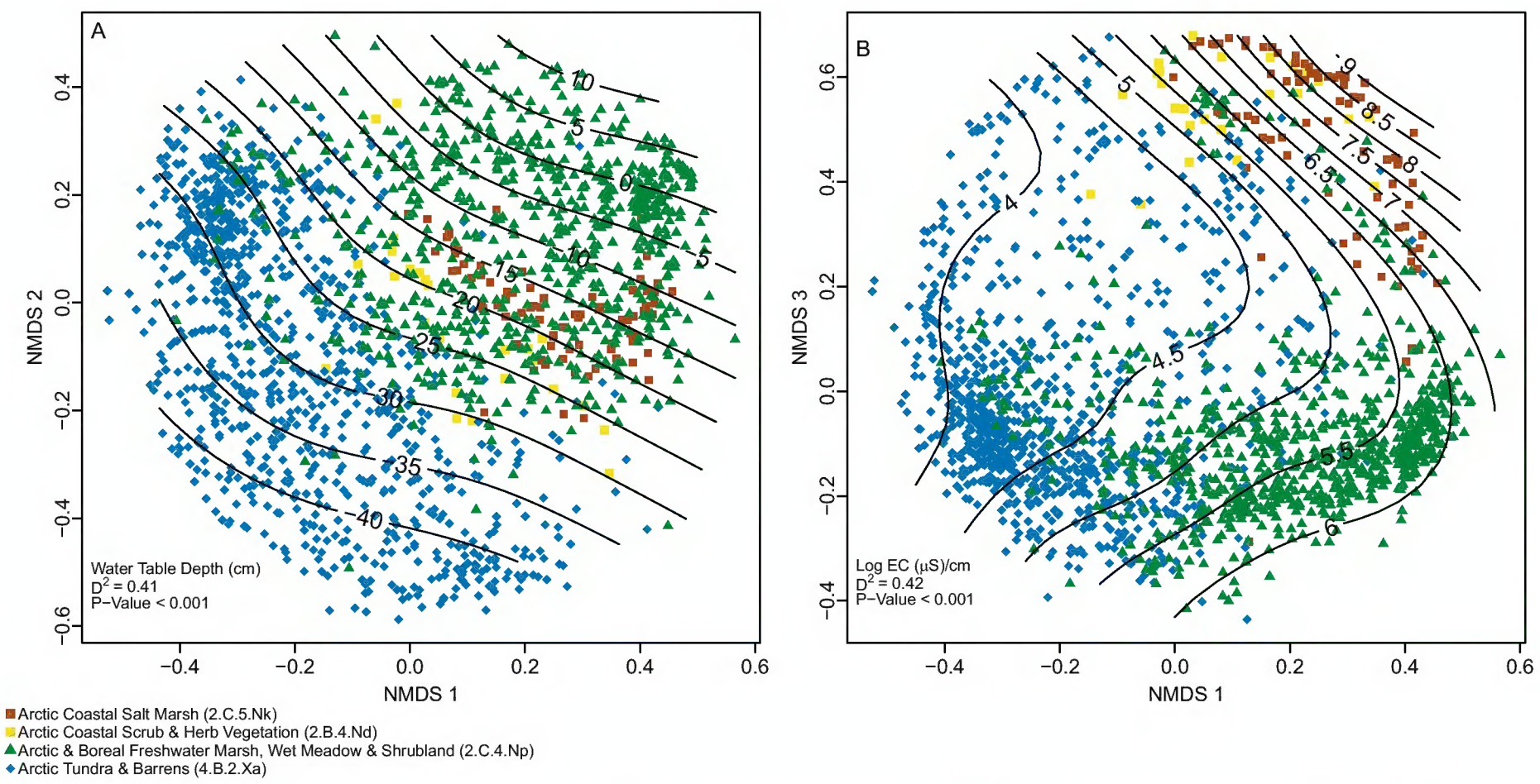


Figure 3. Non-metric Multidimensional Scaling (NMDS) ordination of all Arctic plots from the ELD with USNVC divisions symbolized and with fitted Generalized Additive Model (GAM) surfaces overlaid to illustrate the relationships between plant species composition and gradients in water table depth and electrical conductivity (EC), ELD Arctic association classification, Alaska.

axis scores, respectively. Thinner surface organic layers and deeper active layers were predicted on the upper ends of axis 1 and 2, corresponding to Arctic Scree, Rock & Cliff Barrens; while the thickest surface organic layers and shallowest active layers were predicted on the lower ends of axes 1 and 2, corresponding to a subset of plots in Arctic Dry-Moist Tundra. A pH gradient is also reflected in the NMDS with predicted pH increasing along axis 1. The distribution of plots in the NMDS based on plant species composition also reflects patterns in vegetation structure ($p < 0.001$) and physiography as represented by the USNVC Groups (Figure 4D). Plots located in Alpine physiography are clustered near the center of the ordination and represent about half of the plots in the Dwarf Shrub Tundra Group, and nearly all of the plots in the Arctic Lichen Barrens (G868) and Arctic Open Scree, Rock, & Cliff Barrens (G869) Groups (Figure 4D). Figure 4D also shows that the two barrens Groups are distinct from the Arctic Gravel Floodplain Vegetation Group (G616).

The NMDS analysis of low and tall willow vegetation revealed three clearly differentiated ($p < 0.001$) macrogroups (Figure 5A). Two of the macrogroups, Arctic Dry-Moist Tundra (M173) and Arctic Scree, Rock, & Cliff Barrens (M175), are from the Arctic Tundra & Barrens Division. Arctic Dry-Moist Tundra encompasses moist low willow vegetation in uplands and on upper floodplain positions, while Arctic Scree, Rock, & Cliff Barrens encompasses low and tall willow vegetation on

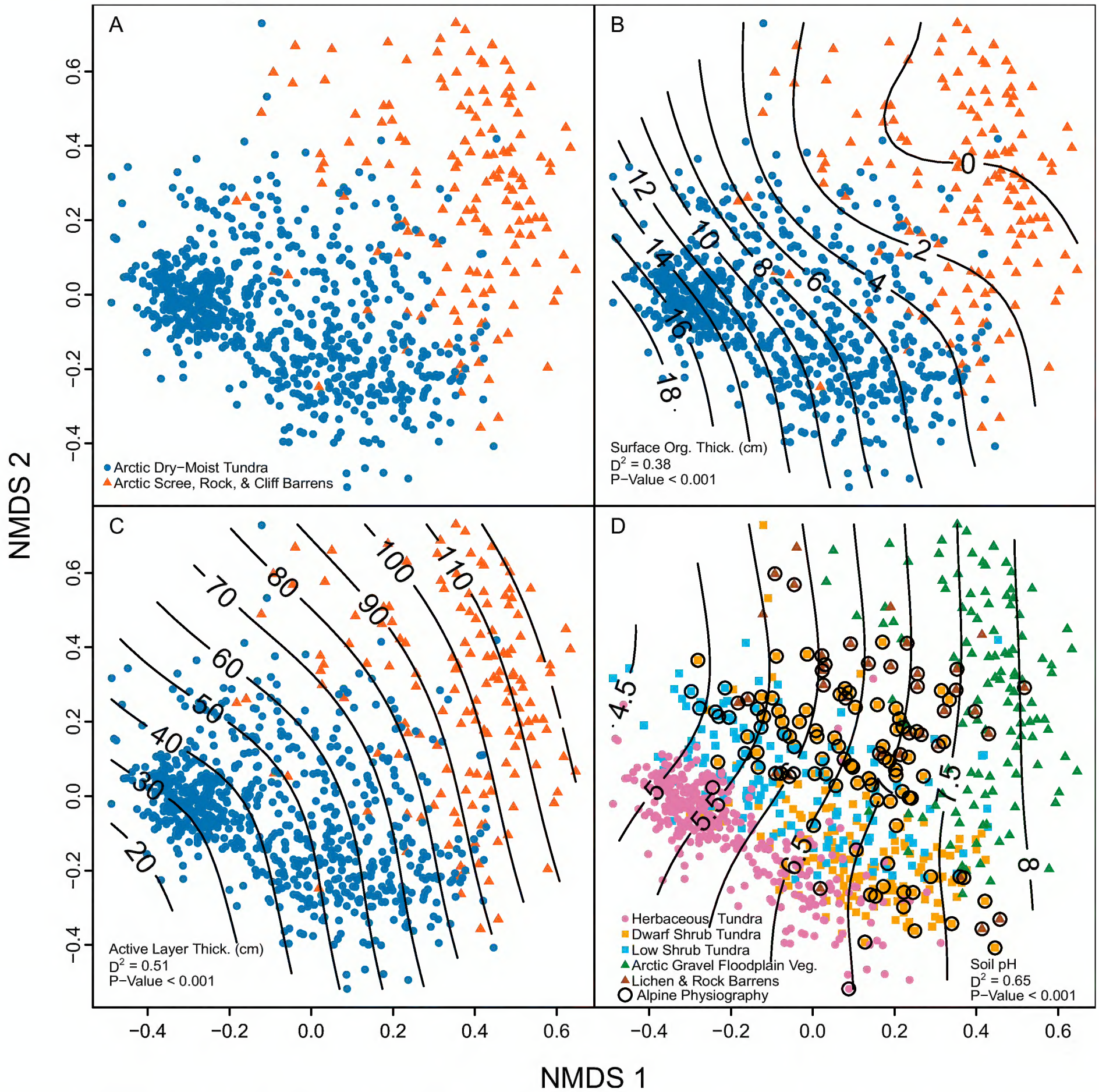
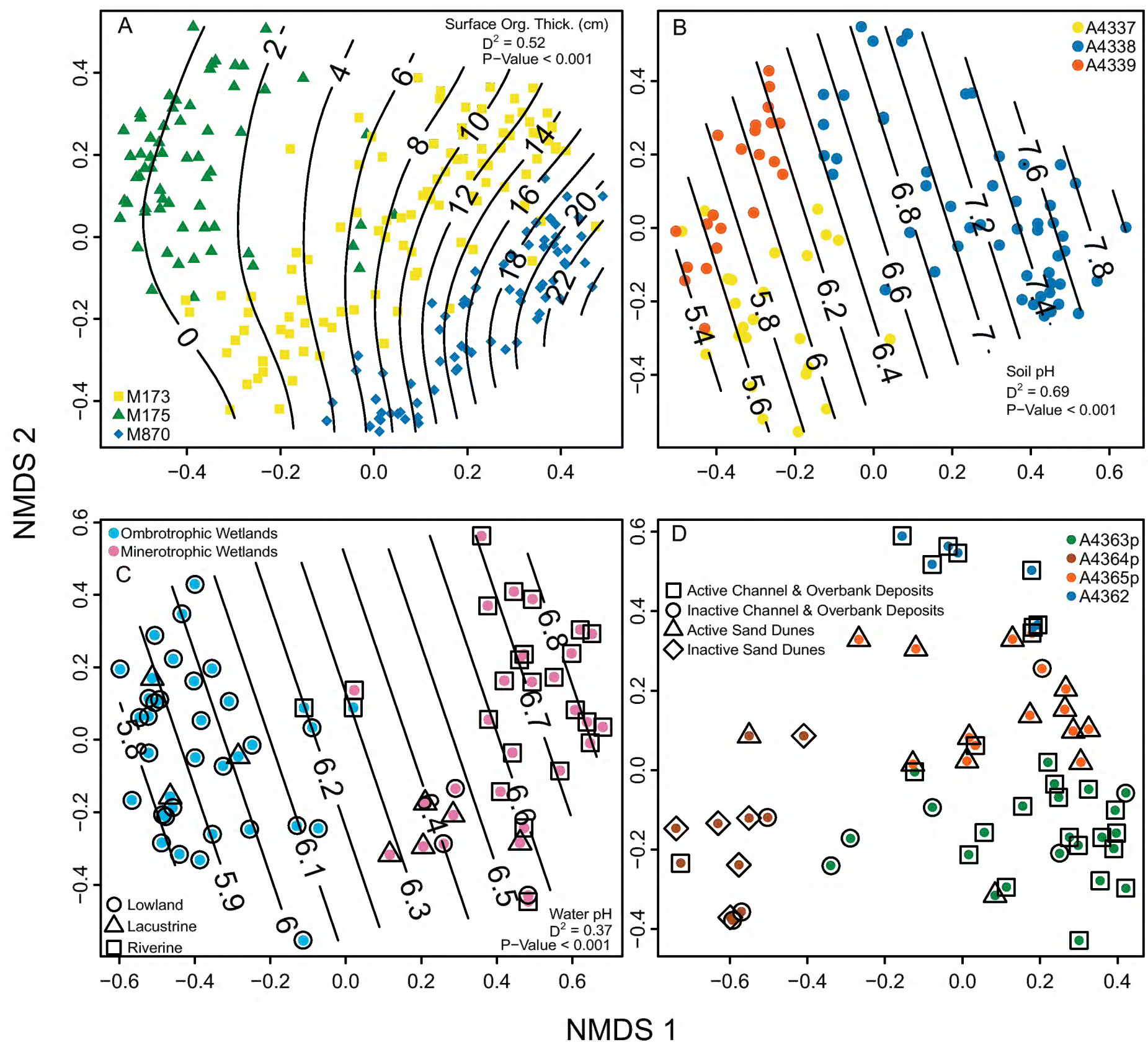


Figure 4. Non-metric Multidimensional Scaling (NMDS) ordination of plots in the Arctic Tundra & Barrens Division (4.B.2.Xa) symbolized by macrogroup (panels **A–C**) and group (panel **D**) with fitted Generalized Additive Model (GAM) surfaces overlaid to illustrate the relationships between plant species composition and environmental gradients, ELD Arctic association classification, Alaska.

river bars, lower floodplain positions, and inland dunes related along a successional sequence from barrens to low and tall willow shrublands. The third macrogroup, Arctic Freshwater Marsh, Wet Meadow & Shrubland (M870), represents low and tall willow wetlands under Arctic Freshwater Marsh & Wet Meadow. The GAM of surface organic thickness explained 52% of the deviance in the distribution of plots across the NMDS axis scores. Thinner surface organic layers were predicted on the lower end of axis 1, corresponding primarily to Arctic Scree, Rock & Cliff Barrens, while the thickest surface organic layers were predicted on the upper end of axis 1, corresponding to Arctic Freshwater Marsh, Wet Meadow & Shrubland and a small subset of plots in Arctic Dry-Moist Tundra .

Groups and alliances: low and tall willow

Figures 5B, C, D display NMDS ordinations for subsets of the low and tall willow plots corresponding to three USNVC Groups: Arctic Low Shrub Tundra (G897, Figure 5B), North America Arctic Wet Shrubland (G830, Figure 5C), and Arctic Gravel Floodplain Vegetation (G616, Figure 5D). In each panel, the plots are symbolized by USNVC alliance. The NMDS for Arctic Dry-Moist Tundra (Figure 5B) displays three tight groupings ($p < 0.001$) of plots by alliance: Arctic Acidic Low Willow Tundra Alliance (A4337), Arctic Nonacidic Low Willow Tundra Alliance (A4338), and Arctic Dwarf Birch Low Shrub Tundra Alliance (A4339). The silhouette analysis confirmed the

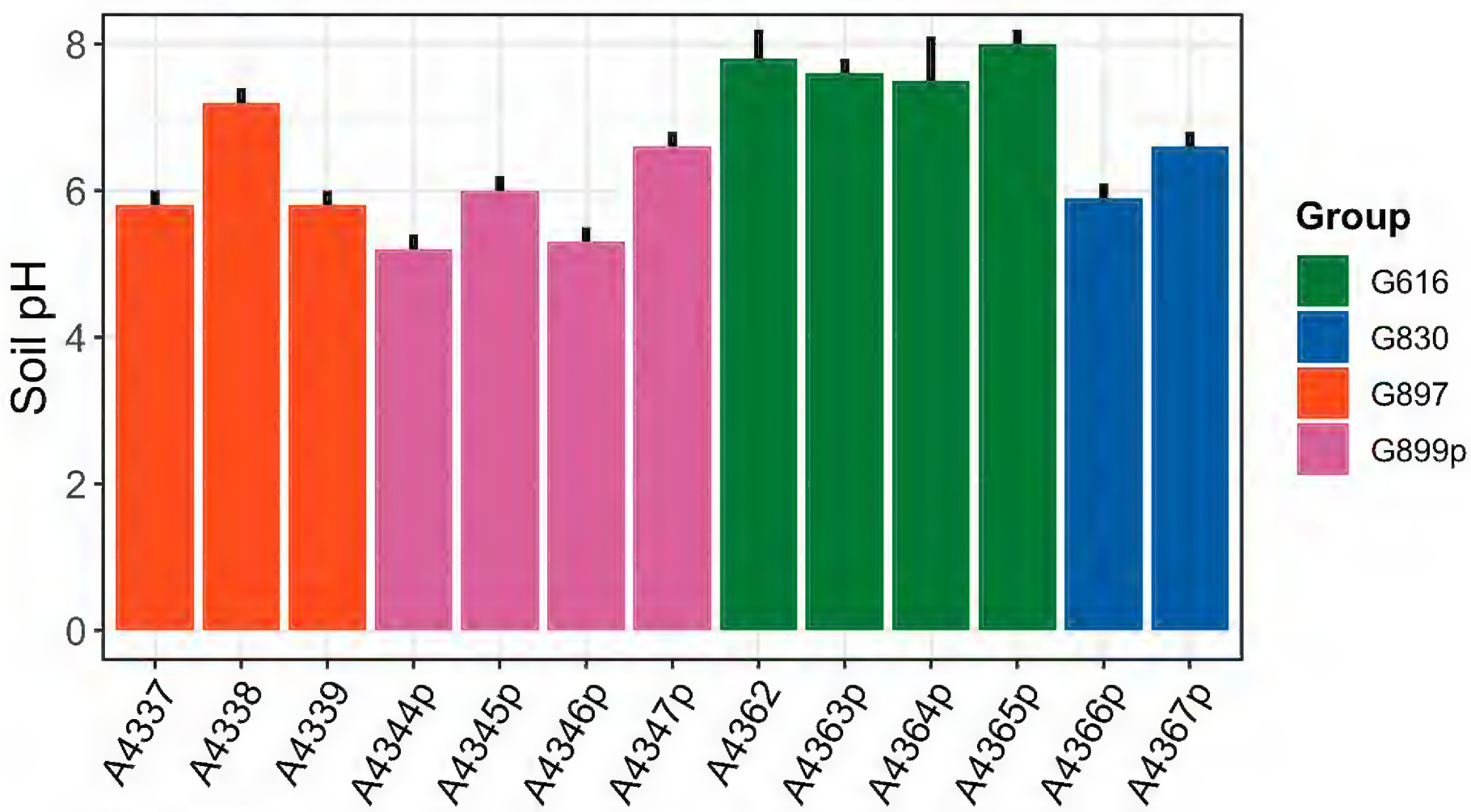


A4337: Arctic Acidic Low Willow Tundra All.
A4338: Arctic Nonacidic Low Willow Tundra All.
A4339: Arctic Dwarf Birch Low Shrub Tundra All.
A4362: *Chamerion latifolium − Salix alaxensis* Arctic Fldpn. All.
A4363p: *Salix alaxensis* River Bar All.
A4364p: *Salix glauca* River Bar & Dune All.
A4365p: *Salix alaxensis − Salix niphoclada* River Bar & Dune All.
M173: Arctic Dry−Moist Tundra Mg.
M175: Arctic Scree, Rock & Cliff Barrens Mg.
M870: Arctic Freshwater Marsh, Wet Meadow & Shrubland Mg.

Figure 5. Non-metric Multidimensional Scaling (NMDS) ordination of low and tall willow plots symbolized by macrogroup, alliance, and geomorphic unit with fitted Generalized Additive Model (GAM) surfaces overlaid to illustrate the relationships between plant species composition and environmental gradients, ELD Arctic association classification, Alaska.

three groupings best maximized the within to between cluster similarity (Suppl. material 2C). The GAM of soil pH explained 69% of the deviance in the distribution of plots across the NMDS axis scores. Lower pH soils are predicted on the lower end of axis 1, corresponding to Arctic Acidic Low Willow Tundra and Arctic Dwarf Birch Low Shrub Tundra, while higher pH soils are predicted on the upper end of axis 1, corresponding to Arctic Nonacidic Low Willow Tundra. Figure 6 demonstrates the clear distinctions in pH between Arctic Acidic Low Willow Tundra (5.8 ± 0.5) and Arctic Dwarf Birch Low Shrub Tundra (5.8 ± 0.6), and Arctic Nonacidic Low Willow Tundra (7.2 ± 0.7). Table 3 displays the low and tall willow alliances within the USNVC hierarchy, Table 4 provides descriptions for each alliance, and Figure 7 displays representative photos of each alliance.

The NMDS for North America Arctic Wet Shrubland (Figure 5C) and silhouette diagram (Suppl. material 2D) display two discrete groupings ($p < 0.001$) of plots corresponding to ombrotrophic and minerotrophic wetlands. The GAM of water pH has a moderately low fit ($D^2 = 0.37$), with higher pH predicted on the upper end of axis 1, corresponding to minerotrophic wetlands, and lower pH predicted on the lower end of axis 1, corresponding to ombrotrophic wetlands. The distribution of plots in the NMDS also reflects patterns in physiography ($p < 0.001$), with minerotrophic wetlands occurring in riverine and lacustrine physiography, and ombrotrophic wetlands predominantly in lowland physiography. Two alliances currently exist within the North America Arctic Wet Shrubland Group: *Betula nana - Ericaceous* Arctic Wet Shrubland Alliance (A4359) and Arctic Willow Wet Shrubland Alliance (A4358). Our analysis has identified two alliances that roughly overlap in concept with the two existing alliances and correspond to ombrotrophic and minerotrophic shrub wetlands, respectively (Figure 5C). The *Betula nana - Ericaceous* Arctic Wet Shrubland Alliance corresponds in part to the ombrotrophic shrub wetlands and the Arctic Willow Wet Shrubland Alliance encompasses both ombrotrophic and minerotrophic shrub wetlands. We propose renaming the two existing alliances to broaden the concept of *Betula nana - Ericaceous* Arctic Wet Shrubland slightly to allow for low willow vegetation, and to differentiate the concepts of the two alliances on hydrology and water chemistry. We propose the following name changes: 1) *Betula nana - Ericaceous* Arctic Wet Shrubland changes to Arctic Ombrotrophic Wet Low Shrublands Alliance Proposed (A4366p), and 2) Arctic Willow Wet Shrubland Alliance changes to Arctic Minerotrophic Wet Low Shrublands Alliance Proposed (A4367p). Since the concepts of proposed alliances are slightly different than the existing alliances, for the



Codes Explained

A4337: Arctic Acidic Low Willow Tundra All.
A4338: Arctic Nonacidic Low Willow Tundra All.
A4339: Arctic Dwarf Birch Low Shrub Tundra All.
A4344p: Arctic Acidic Shrub Tussock Tundra All.
A4345p: Arctic Nonacidic Shrub Tussock Tundra All.
A4346p: Arctic Acidic Tussock Tundra All.
A4347p: Arctic Nonacidic Tussock Tundra All.
A4362: *Chamerion latifolium - Salix alaxensis* Arctic Fldpn. All.
A4363p: *Salix alaxensis* River Bar All.
A4364p: *Salix glauca* River Bar & Dune All.
A4365p: *Salix alaxensis - Salix niphoclada* River Bar & Dune All.
A4366p: Arctic Ombrotrophic Wet Low Shrublands All.
A4367p: Arctic Minerotrophic Wet Low Shrublands All.
G616: Arctic Gravel Floodplain Vegetation Group
G830: North American Arctic Wet Shrubland Group
G897: Arctic Low Shrub Tundra Group
G899p: Arctic Herbaceous Tussock Tundra Group

Figure 6. Barchart of soil pH with standard error bars by USNVC alliance, ELD Arctic association classification, Alaska.

Figure 7. Representative photos of low/tall willow and tussock tundra alliances, ELD Arctic association classification, Alaska.

remainder of this manuscript we refer to our proposed new titles and codes for these classes to clearly differentiate them from the existing titles and codes.

The NMDS and silhouette diagram for Arctic Gravel Floodplain Vegetation (Figure 5D, Supp. material 2E) displays four distinct plot groupings ($p < 0.001$). The four groupings correspond to one existing and three proposed alliances: *Chamerion latifolium* - *Salix alaxensis* Arctic Floodplain Alliance (A4362), *Salix alaxensis* River Bar Alliance Proposed (A4363p), *Salix glauca* River Bar & Dune Alliance Proposed (A4364p), and *Salix alaxensis* - *Salix niphoclada* River Bar & Dune Alliance Proposed (A4365p). The distribution of plots in the NMDS also reveals landform affinities by alliance. For instance, *Chamerion latifolium* - *Salix alaxensis* Arctic Floodplain and *Salix alaxensis* River Bar Proposed occur almost exclusively on Active Channel and Overbank Deposits, *Salix alaxensis* - *Salix niphoclada* River Bar & Dune Proposed occurs almost entirely on Active Sand Dunes, and *Salix glauca* River Bar & Dune Proposed occurs most frequently on Inactive Sand Dunes.

Groups and alliances: tussock tundra

Figure 8A displays the NMDS of the Arctic Dry-Moist Tundra Macrogroup with USNVC group symbolized. The Arctic Herbaceous Tundra Group (G898) is further

Table 2. Taxa not recognized by USDA NRCS (2021), and the number of plots each occurs in from the ELD Arctic plant association classification, Alaska.

Scientific Name	Plot count
Androsace chamaejasme subsp. *lehmannia*	27
Astragalus aboriginum	6
Astragalus eucosmus subsp. *eucosmus*	5
Bryoerythrophyllum recurvirostrum	1
Calamagrostis purpurascens subsp. *purpurascens*	21
Cerastium beeringianum var. *beeringianum*	6
Coeloglossum viride subsp. *viride*	1
Dicranum flexicaule	2
Drepanocladus sordidus	2
Eriophorum russeolum subsp. *leiocarpum*	2
Gentiana propinqua subsp. *propinqua*	34
Hypnum holmenii	2
Iris setosa subsp. *setosa*	1
Lagotis glauca subsp. *glauca*	24
Lathyrus maritimus subsp. *maritimus*	4
Lophozia silvicola	2
Luzula wahlenbergii subsp. *wahlenbergii*	9
Mertensia maritima subsp. *maritima*	3
Nostoc pruniforme	1
Pedicularis kanei subsp. *kanei*	46
Phlox sibirica subsp. *sibirica*	7
Poa sublanata	5
Ranunculus gmelinii subsp. *gmelinii*	3
Sphagnum imbricatum	5
Sphagnum tundrae	3
Therorhodion camtschaticum	2

symbolized to visualize tussock tundra and nontussock tundra plots within this group. In Figure 8A the Arctic Herbaceous Tundra tussock plots are well differentiated, as are most of the Arctic Dwarf plots. However, the Arctic Low Shrub Tundra plots have a high degree of overlap with both Arctic Dwarf Shrub Tundra and Arctic Herbaceous Tundra nontussock plots, specifically in the lower right corner of the ordination. This is also illustrated in the silhouette diagram which displays a low silhouette width (0.01) for the Arctic Low Shrub Tundra Group (Suppl. material 2F). The low silhouette width is caused by a high number of reversals, or plots with a negative silhouette width indicating that they fit better in another cluster. About half of these plots are dwarf birch (*Betula nana*) and willow low shrub communities with abundant dwarf ericaceous shrubs. The high cover of dwarf ericaceous shrubs relative to the cover of low shrubs makes these plots appear more similar to Arctic Dwarf Shrub Tundra in the silhouette analysis. The GAM of soil pH explained 59% of the deviance in the distribution of plots across the NMDS axis scores with pH predicted to increase along Axis 1. Ordinating only the Arctic Low Shrub Tundra and Arctic Herbaceous Tundra plots revealed clear distinctions between groups and between tussock and nontussock tundra within Arctic Herbaceous Tundra (Figure 8B, C). The results of the GAMs indicate that the groups are distinguished across gradients of active

Table 3. Low and tall willow and tussock tundra associations (N ≥ 4) and community types (N < 4), and sample sizes from the ELD Arctic plant association classification nested within the USNVC hierarchy, Alaska. N: number of plots.

Class/Subclass/Formation/Division/Macrogroup/Group/Alliance	Association or Community Type	N
2: Shrub & Herb Vegetation Class		
2.C: Shrub & Herb Wetland Subclass		
2.C.4: Temperate to Polar Freshwater Marsh, Wet Meadow & Shrubland Formation		
2.C.4.Np: Arctic & Boreal Freshwater Marsh, Wet Meadow & Shrubland		
M870: Arctic Freshwater Marsh, Wet Meadow & Shrubland		
G830: North American Arctic Wet Shrubland		
A4366p: Arctic Ombrotrophic Wet Low Shrublands (proposed)	*Betula nana–Salix pulchra/Carex aquatilis–Eriophorum angustifolium*	7
	Salix pulchra/Carex aquatilis	1
	Salix pulchra/Carex aquatilis–Comarum palustre	2
	Salix pulchra/Carex aquatilis–Eriophorum angustifolium	4
	Salix pulchra/Carex aquatilis–Eriophorum angustifolium–Saxifraga hirculus	9
	Salix pulchra/Carex aquatilis–Eriophorum angustifolium/Sphagnum	10
	Salix pulchra/Eriophorum angustifolium	6
A4367p: Arctic Minerotrophic Wet Low Shrublands (proposed)	*Salix richardsonii/Carex aquatilis–Eriophorum angustifolium*	23
	Salix richardsonii/Equisetum variegatum	9
4: Polar & High Montane Scrub, Grassland & Barrens Class		
4.B: Temperate to Polar Alpine & Tundra Vegetation Subclass		
4.B.2: Polar Tundra & Barrens Formation		
4.B.2.Xa: Arctic Tundra & Barrens Division		
M173: Arctic Dry-Moist Nontussock Tundra		
G897: Arctic Low Shrub Tundra		
A4337: Arctic Acidic Low Willow Tundra Alliance	*Salix pulchra/Carex bigelowii*	9
	Salix pulchra/Equisetum arvense	3
	Salix pulchra/Hylocomium splendens	1
	Salix pulchra/Petasites frigidus	7

Class/Subclass/Formation/Division/Macrogroup/Group/Alliance	Association or Community Type	N
	Salix pulchra–Vaccinium uliginosum	2
A4338: Arctic Nonacidic Low Willow Tundra Alliance	*Salix glauca/Arctagrostis latifolia*	2
	Salix glauca/Dryas integrifolia/Carex bigelowii	5
	Salix glauca/Dryas integrifolia/Rhytidium rugosum	5
	Salix glauca/Lupinus arcticus	3
	Salix richardsonii/Arctostaphylos rubra	16
	Salix richardsonii/Equisetum arvense	3
	Salix richardsonii/Equisetum arvense–Festuca altaica	5
	Salix richardsonii/Equisetum arvense–Petasites frigidus	13
A4339: Arctic Dwarf Birch Low Shrub Tundra Alliance	*Betula nana–Salix glauca/Vaccinium vitis-idaea/Carex bigelowii*	5
	Betula nana–Salix glauca/Vaccinium vitis-idaea/Saussurea angustifolia	7
	Betula nana–Salix pulchra/Petasites frigidus	10
G899p: Arctic Herbaceous Tussock Tundra (proposed)		
A4344p: Arctic Acidic Shrub Tussock Tundra Alliance (proposed)	*Alnus viridis ssp. fruticosa/Betula nana/Eriophorum vaginatum*	14
	Betula nana–Ledum palustre ssp. decumbens/Eriophorum vaginatum	77
	Ledum palustre ssp. decumbens/Eriophorum vaginatum	31
A4345p: Arctic Nonacidic Shrub Tussock Tundra Alliance (proposed)	*Betula nana–Salix pulchra/Eriophorum vaginatum*	31
	Salix pulchra/Eriophorum vaginatum	27
A4346p: Arctic Acidic Tussock Tundra Alliance (proposed)	*Eriophorum vaginatum/Ledum palustre ssp. decumbens–Vaccinium vitis-idaea*	45
	Eriophorum vaginatum/Vaccinium uliginosum/Sphagnum	5
A4347p: Arctic Nonacidic Tussock Tundra Alliance (proposed)	*Eriophorum vaginatum/Dryas integrifolia*	31
M175: Arctic Scree, Rock & Cliff Barrens		
G616: Arctic Gravel Floodplain Vegetation		
A4362: *Chamerion latifolium - Salix alaxensis* Arctic Floodplain Alliance	*Salix alaxensis/Chamerion latifolium*	8
A4363p: *Salix alaxensis* River Bar Alliance (proposed)	*Salix alaxensis/Dryas integrifolia*	1
	Salix alaxensis/Equisetum arvense	11
	Salix alaxensis/Eurybia sibirica	8
	Salix alaxensis/Hedysarum boreale ssp. mackenziei	1
	Salix hastata–Salix alaxensis/Equisetum variegatum	4
A4364p: *Salix glauca* River Bar & Dune Alliance (proposed)	*Salix glauca/Arctostaphylos rubra*	8
	Salix glauca/Koeleria asiatica	3
A4365p: *Salix alaxensis - Salix niphoclada* River Bar & Dune Alliance (proposed)	*Salix alaxensis/Arctostaphylos rubra*	1
	Salix alaxensis/Artemisia campestris ssp. borealis var. borealis	1
	Salix alaxensis/Tanacetum bipinnatum ssp. bipinnatum	13
	Salix niphoclada–Salix alaxensis/Arctous rubra	4

layer thickness (Figure 8B) and tussock cover (Figure 8C), with the shallowest active layers and highest tussock cover in tussock tundra. The NMDS analysis of the Arctic Herbaceous Tundra plots shows a clear distinction between tussock and nontussock tundra (Figure 8D). The silhouette diagram compliments the ordination analysis and displays two distinct clusters representing tussock and non-tussock tundra (Suppl. material 2G). The exceptions are a handful of tussock tundra plots more like the non-tussock tundra cluster, all of which were non-acidic tussock tundra. The GAM of soil pH had a strong fit ($D^2 = 0.54$) and predicted a decreasing pH gradient along NMDS axis 1. Nontussock tundra generally corresponded with areas of the NMDS predicted to have alkaline soils, while tussock tundra ranged from circum-alkaline to acidic soils. Given the clear distinction between tussock and non-tussock tundra demonstrated above we propose that Arctic Herbaceous Tundra gets split into tussock and nontussock tundra Groups. For the remainder of the manuscript we will use the following titles and codes when referencing these proposed Groups: Arctic Herbaceous Tussock Tundra Proposed (G899p) and Arctic Herbaceous Nontussock

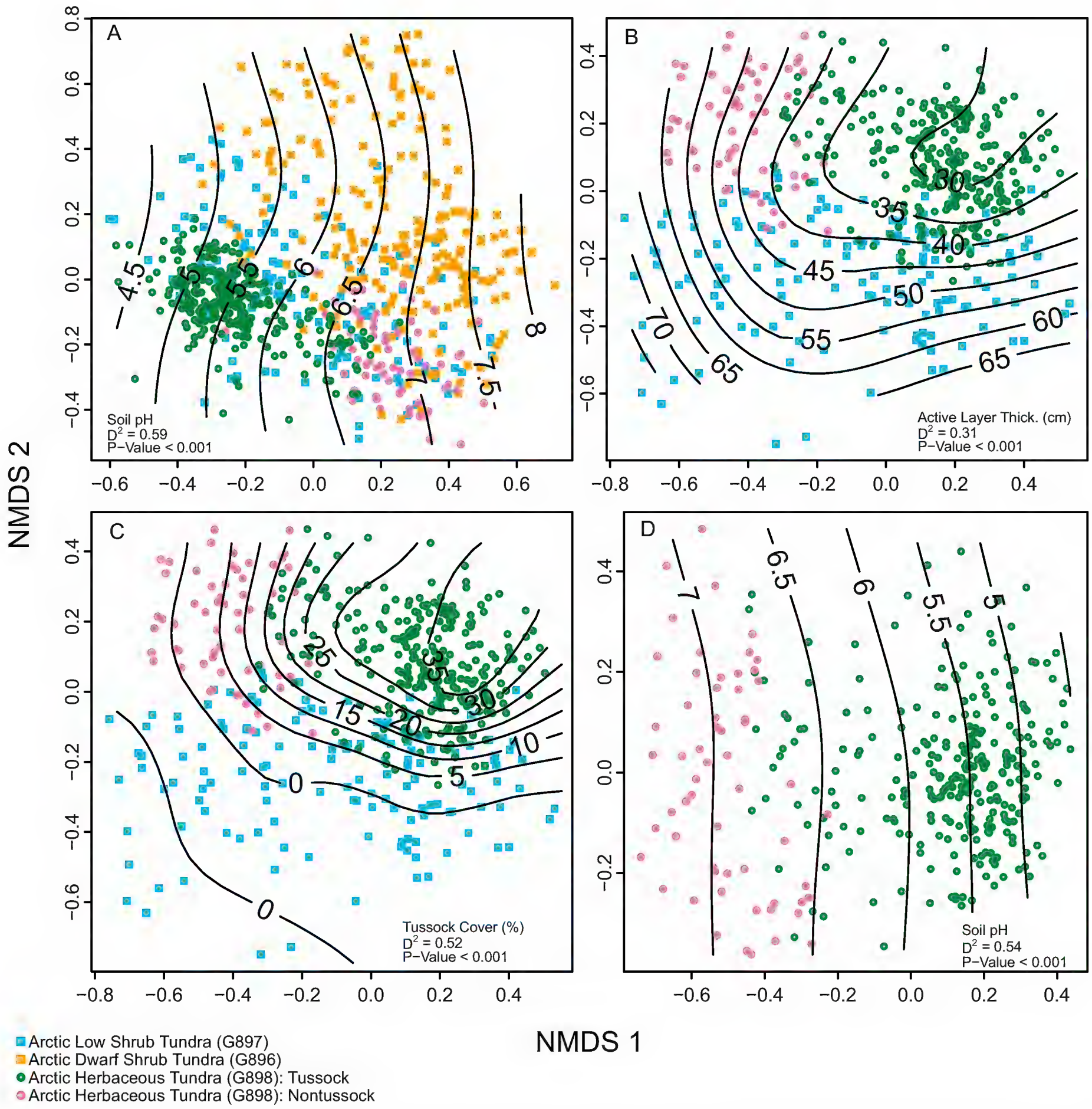


Figure 8. Non-metric Multidimensional Scaling (NMDS) ordination of plots in the Arctic Dry-Moist Tundra Macrogroup (M173) with groups symbolized and with fitted Generalized Additive Model (GAM) surfaces overlaid to illustrate the relationships between plant species composition and environmental gradients, ELD Arctic association classification, Alaska.

Tundra Proposed (G898p). The NMDS analysis of the plots from Arctic Herbaceous Tussock Tundra Proposed displays four distinct ($p < 0.001$) groupings corresponding to the following proposed alliances (Figure 9A SM 2H): Arctic Acidic Shrub Tussock Tundra Alliance Proposed (A4344p), Arctic Nonacidic Shrub Tussock Tundra Alliance Proposed (A4345p), Arctic Acidic Tussock Tundra Alliance Proposed (A4346p), and Arctic Nonacidic Tussock Tundra Alliance Proposed (A4347p). Table 3 displays the shrub tussock and tussock tundra alliances within the USNVC hierarchy, Table 4 provides descriptions for each alliance, and Figure 7 displays representative photos of each alliance.

The GAM of soil pH (Figure 9A) explained 42% of the deviance in the distribution of plots across the NMDS axis scores and illustrates distinctions between the acidic and nonacidic tussock tundra alliances. The differences in shrub cover between the shrub tussock tundra and tussock tundra are illustrated in Figure 10, which displays stacked bar charts of foliar cover of vegetation structure classes by alliance. Arctic Acidic Shrub Tussock Tundra Proposed and Arctic Nonacidic Shrub Tussock Tundra Proposed have greater dwarf and low shrub cover, and greater live cover overall (largely driven by shrub cover), than Arctic Acidic Tussock Tundra Proposed and Arctic Nonacidic Tussock Tundra Proposed. The GAM of proportional

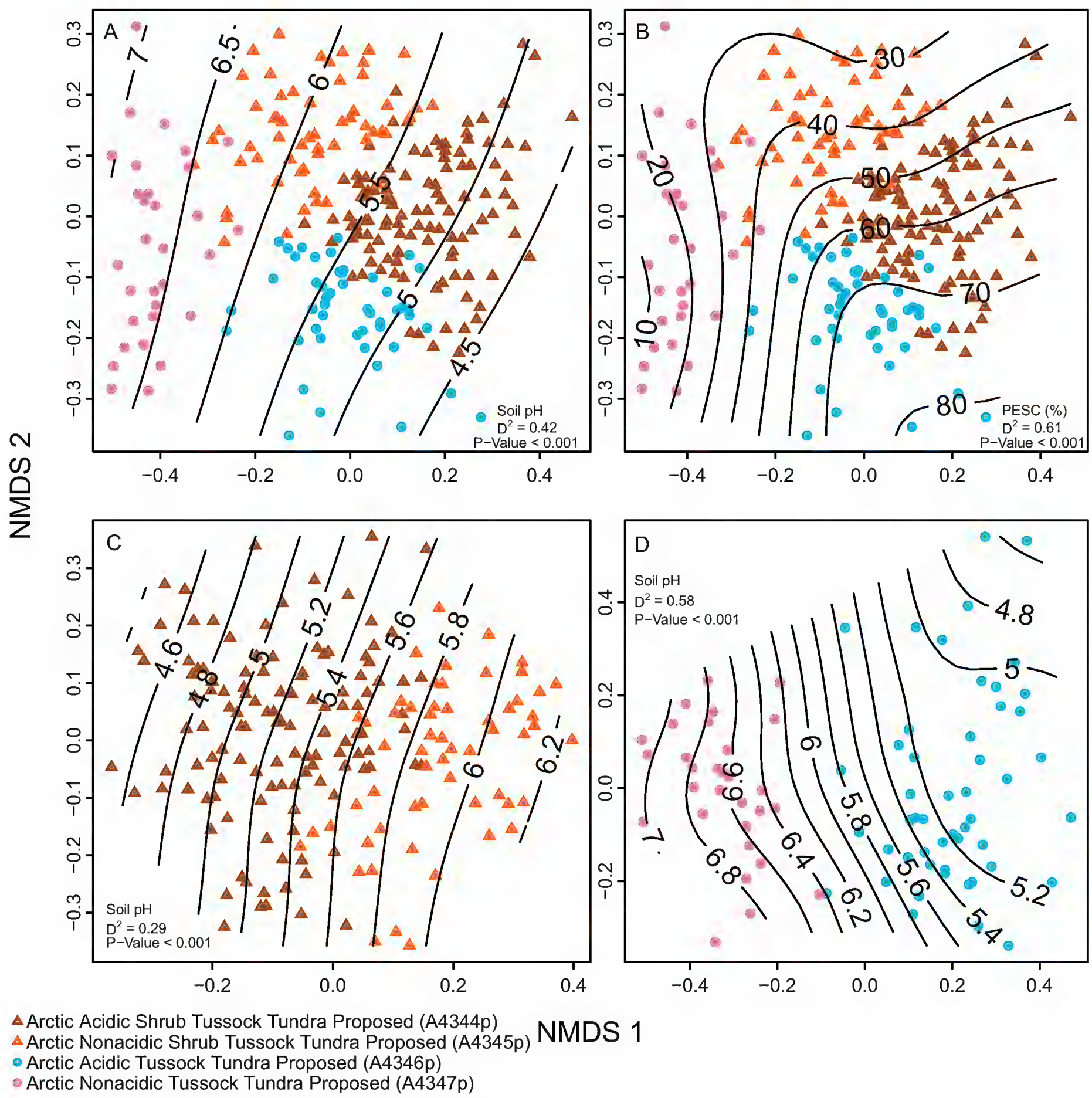


Figure 9. Non-metric Multidimensional Scaling (NMDS) ordination of tussock tundra plots symbolized by alliance with fitted Generalized Additive Model (GAM) surfaces overlaid to illustrate the relationships between plant species composition and environmental gradients, including soil pH and the proportional cover of ericaceous shrubs as a percent of total shrub cover (PESC), ELD Arctic association classification, Alaska.

cover of ericaceous shrubs (PESC), that is, the proportion of total shrub cover accounted for by ericaceous shrubs was strong ($D^2 = 0.61$) and significant ($p < 0.001$, Figure 9B). PESC displayed an inverse relationship with the ordination axis scores related to soil pH (i.e., as PESC is predicted to increase, soil pH is predicted to decrease).

The NMDS ordinations of the shrub tussock tundra plots (Figure 9C) and tussock tundra plots (Figure 9D) show clear distinctions ($p < 0.001$) between the proposed alliances. The soil pH GAMs for both the shrub tussock and tussock tundra alliances are highly significant. However, the fit is moderately weak ($D^2 = 0.29$) for the shrub tussock tundra plots, whereas the fit for the tussock tundra plots is much higher ($D^2 = 0.58$). Figure 6 illustrates the clear distinction in average soil pH by alliance.

Associations

We identified 138 peer-reviewed associations ($n \geq 4$) and 151 plant community types ($n < 4$). A complete list of associations and community types is not provided here as the focus of this manuscript is on the low and tall willow and tussock tundra associations. Of the total associations, 13 were Boreal, defined as those associations in which > 50% of the plots were assigned to the Boreal ecoregion.

Table 4. Descriptions of the low and tall willow and tussock tundra alliances from the ELD Arctic plant association classification, Alaska. Codes with a "p" at the end of the code are proposed Alliances.

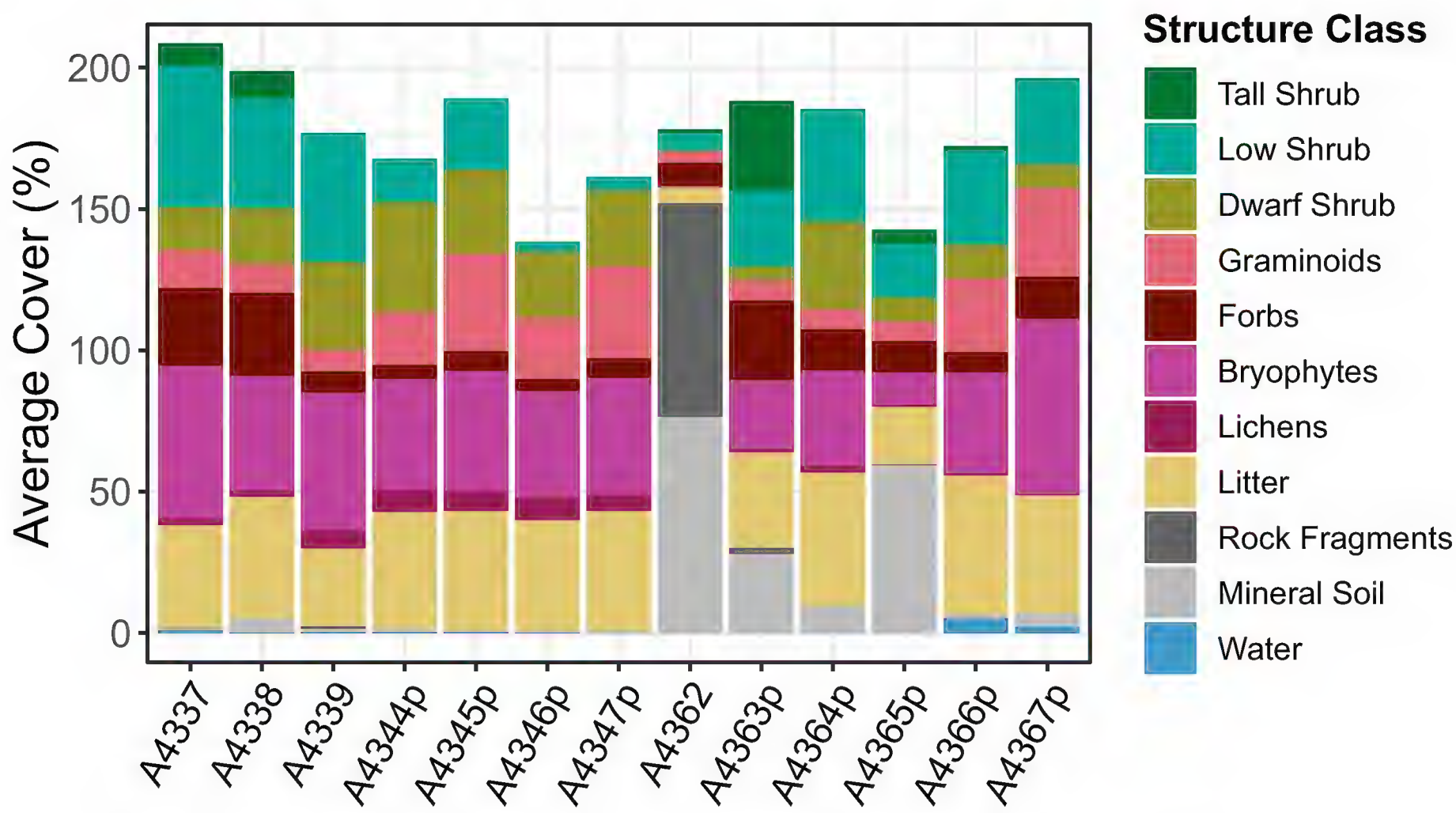
Alliance Code	Alliance Title	Description
A4337	Arctic Acidic Low Willow Tundra Alliance	The Arctic Acidic Low Willow Tundra Alliance (A4337) occurs in Lowland and Upland physiography most commonly on the following geomorphic units: Hillside Colluvium; Loess, Moraine, older; and Solifluction Deposit. The average elevation in this Alliance is 254 m (±312 m), and the slope gradient typically ranges between flat and strongly sloping. This Alliance was commonly associated with the surface form Nonpatterned but is also regularly associated with Hummocks; Undifferentiated mounds; and Non-sorted Circles, boils and scars. Soils are somewhat poorly drained to moderately well drained, surface organic thickness typically ranges from very thin to moderately thick, and coarse fragments are uncommon, but when they do occur the top depth is 86 cm (±85 cm). Permafrost was common, with an average active layer thickness of 41 cm (±17 cm). Soil pH typically ranges from acidic to circumacidic, and the average electrical conductivity is 92 µS/cm (±123 µS/cm). The most common vegetation types include Open Low Willow, Closed Low Willow, and Open Tall Willow. The vegetation is dominated by *Salix pulchra* in the low shrub layer, and *Petasites frigidus* is the most common and abundant herbaceous species. Other common plants include the shrubs *Vaccinium uliginosum, Betula nana, Salix reticulata, Ledum decumbens*, and *Vaccinium vitis-idaea*, and the herbs *Poa arctica, Carex bigelowii, Valeriana capitata, Arctagrostis latifolia, Equisetum arvense, Polemonium acutiflorum*, and *Rubus chamaemorus*. *Carex aquatilis* and *Eriophorum angustifolium* are common in wet microlows at low abundance. The most common and abundant bryophytes include *Hylocomium splendens*, *Aulacomnium palustre*, and *Tomentypnum nitens*; and the lichen *Peltigera aphthosa* is often present at low abundance.
A4338	Arctic Nonacidic Low Willow Tundra Alliance	The Arctic Nonacidic Low Willow Tundra Alliance (A4338) occurs in Riverine and Upland physiography most commonly on the following geomorphic units: Hillside Colluvium, Meander Active Overbank Deposit, and Delta Active Overbank Deposit. The average elevation in this Alliance is 117 m (±160 m), and the slope gradient typically ranges between flat and gently sloping. This Alliance was commonly associated with the surface form Nonpatterned but is also regularly associated with Hummocks and Gelifluction Lobes. Soils are somewhat poorly drained to moderately well drained, surface organic thickness typically ranges from absent to thin, and coarse fragments are uncommon, but when they do occur the top depth is 54 cm (±55 cm). Permafrost was common, with an average active layer thickness of 67 cm (±27 cm). Soil pH typically ranges from circumalkaline to alkaline, and the average electrical conductivity is 273 µS/cm (±263 µS/cm). The most common vegetation types include Open Low Willow and Closed Low Willow. The vegetation is dominated by *Salix richardsonii* or *S. glauca* in the low shrub layer, and *Equisetum arvense* and *Lupinus arcticus* are the most common and abundant herbaceous species. Other common plants include the shrubs *Salix reticulata*, *Arctous rubra*, and *Dryas integrifolia*, and the herbs *Valeriana capitata*, *Polygonum viviparum*, *Arctagrostis latifolia*, *Petasites frigidus*, *Pedicularis capitata*, *Astragalus alpinus*, *Equisetum variegatum*, and *Carex bigelowii*. The most common and abundant bryophytes include *Tomentypnum nitens*, *Hylocomium splendens*, *Campylium stellatum*, and *Rhytidium rugosum*.
A4339	Arctic Dwarf Birch Low Shrub Tundra Alliance	The Arctic Dwarf Birch Low Shrub Tundra Alliance (A4339) occurs in Lowland and Upland physiography most commonly on the following geomorphic units: Hillside Colluvium; Solifluction Deposit; Moraine, older; and Thaw Basin, ice-rich center. The average elevation in this Alliance is 298 m (±369 m), and the slope gradient typically ranges between flat and strongly sloping. This Alliance was commonly associated with the surface form Hummocks but is also regularly associated with Nonpatterned and Non-sorted Circles, boils and scars. Soils are somewhat poorly drained to moderately well drained, surface organic thickness typically ranges from very thin to moderately thick, and coarse fragments are uncommon, but when they do occur the top depth is 89 cm (±96 cm). Permafrost was common, with an average active layer thickness of 34 cm (±14 cm). Soil pH typically ranges from acidic to circumacidic, and the average electrical conductivity is 105 µS/cm (±93 µS/cm). The most common vegetation types are Open Low Shrub Birch-Willow and Closed Low Shrub Birch-Willow. The vegetation is codominated by *Betula nana* and either *Salix pulchra* or *S. glauca* in the low shrub layer, and *Petasites frigidus*, *Carex bigelowii*, and *Arctagrostis latifolia* are the most common and abundant herbaceous species. Other common plants include the shrubs *Vaccinium vitis-idaea*, *Ledum decumbens*, *Vaccinium uliginosum*, *Empetrum nigrum*, and *Cassiope tetragona*, and the herbs *Poa arctica*, *Saussurea angustifolia*, *Polygonum bistorta* ssp. *plumosum*, *Pedicularis capitata*, and *Saxifraga punctata*. The most common and abundant bryophytes and lichens include *Hylocomium splendens*, *Aulacomnium turgidum*, and *Rhytidium rugosum*; and *Flavocetraria cucullata* and *Thamnolia vermicularis*, respectively.
A4344p	Arctic Acidic Shrub Tussock Tundra Alliance	The Arctic Acidic Shrub Tussock Tundra Alliance Proposed (A4344p) occurs in Upland physiography most commonly on the following geomorphic units: Frozen Upland Silt, Upland Loess, and Eolian Sand Sheet Upland. The average elevation in this Alliance is 123 m (±121 m), and the slope gradient typically ranges between flat and gently sloping. This Alliance was commonly associated with the surface forms Nonpatterned and High-centered, Low-relief Polygons, but is also regularly associated with Mixed pits and polygons and High-centered, High-relief Polygons. Soils are poorly drained to somewhat poorly drained, surface organic thickness typically ranges from thin to moderately thick, and coarse fragments are rare. Permafrost was common, with an average active layer thickness of 31 cm (±8 cm). Soil pH typically ranges from acidic to circumacidic, and the average electrical conductivity is 92 µS/cm (±79 µS/cm). The most common vegetation types are Open Mixed Low Shrub-Sedge Tussock Tundra and Tussock Tundra-Ericaceous. The vegetation is dominated by *Betula nana*, *Alnus viridis* ssp. *fruticosa*, or *Ledum decumbens* in the low shrub layer. *Eriophorum vaginatum* is the dominant herbaceous species and forms conspicuous tussocks with a cover of whole tussocks of at least 5%. Other common plants include the shrubs *Vaccinium vitis-idaea*, *Cassiope tetragona*, *Empetrum nigrum*, *Salix pulchra*, and *Vaccinium uliginosum*, and the herbs *Carex bigelowii*, *Polygonum bistorta* ssp. *plumosum*, *Rubus chamaemorus*, *Arctagrostis latifolia*, and *Saussurea angustifolia*. The most common and abundant bryophytes and lichens include *Aulacomnium turgidum*, *Hylocomium splendens*, *Dicranum elongatum*, *Ptilidium ciliare*, and *Sphagnum warnstorfii*; and *Flavocetraria cucullata*, *Dactylina arctica*, *Thamnolia vermicularis*, *Peltigera aphthosa*, and *Cladina arbuscula*, respectively.
A4345p	Arctic Nonacidic Shrub Tussock Tundra Alliance	The Arctic Nonacidic Shrub Tussock Tundra Alliance Proposed (A4345p) occurs in Upland physiography most commonly on the following geomorphic units: Alluvial-Marine Deposit, Eolian Sand Sheet Upland, and Upland Loess. The average elevation in this Alliance is 89 m (±191 m), and the slope gradient typically ranges between flat and gently sloping. This Alliance was commonly associated with the surface forms Nonpatterned and High-centered, Low-relief Polygons, but is also regularly associated with Mixed pits and polygons and High-centered, High-relief Polygons. Soils are poorly drained to somewhat poorly drained, surface organic thickness typically ranges from thin to moderately thick, and coarse fragments are rare. Permafrost was common, with an average active layer thickness of 31 cm (±8 cm). Soil pH typically ranges from circumacidic to circumalkaline, and the average electrical conductivity is 121 µS/cm (±104 µS/cm). The most common vegetation type is Open Mixed Low Shrub-Sedge Tussock Tundra. The vegetation is dominated by *Salix pulchra* or codominated by *S. pulchra* and *Betula nana* in the low shrub layer. *Eriophorum vaginatum* is the dominant herbaceous species and forms conspicuous tussocks with a cover of whole tussocks of at least 5%. Other common plants include the shrubs *Vaccinium vitis-idaea*, *Ledum decumbens*, *Cassiope tetragona*, *Salix reticulata*, and *Dryas integrifolia*, and the herbs *Carex bigelowii*, *Arctagrostis latifolia*, *Polygonum bistorta* ssp. *plumosum*, *Saussurea angustifolia*, and *Poa arctica*. The most common and abundant bryophytes and lichens include *Hylocomium splendens*, *Aulacomnium turgidum*, *Ptilidium ciliare*, *Tomentypnum nitens*, and *Sphaerophorus globosus*; and *Flavocetraria cucullata*, *Dactylina arctica*, *Thamnolia vermicularis*, *Peltigera aphthosa*, and *Cetraria islandica*, respectively.

Alliance Code	Alliance Title	Description
A4346p	Arctic Acidic Tussock Tundra Alliance	The Arctic Acidic Tussock Tundra Alliance Proposed (A4346p) occurs in Upland physiography most commonly on the following geomorphic units: Eolian Sand Sheet Upland; Alluvial-Marine Deposit; and Thaw Basin, ice-rich center. The average elevation in this Alliance is 90 m (±157 m), and the slope gradient typically ranges between flat and gently sloping. This Alliance was commonly associated with the surface forms Nonpatterned and High-centered, Low-relief Polygons, but is also regularly associated with Mixed High and Low-centered Polygons and High-centered, High-relief Polygons. Soils are somewhat poorly drained to moderately well drained, surface organic thickness typically ranges from thin to moderately thick, and coarse fragments are rare. Permafrost was common, with an average active layer thickness of 31 cm (±8 cm). Soil pH typically ranges from acidic to circumacidic, and the average electrical conductivity is 84 µS/cm (±61 µS/cm). The most common vegetation type is Tussock Tundra-Ericaceous. The vegetation is dominated by *Eriophorum vaginatum*, which forms conspicuous tussocks with a cover of whole tussocks of at least 5%. *Vaccinium vitis-idaea* and *Ledum decumbens* are the most common and abundant dwarf shrubs. Other common plants include the shrubs *Cassiope tetragona*, *Betula nana*, *Empetrum nigrum*, and *Vaccinium uliginosum*, and the herbs *Carex bigelowii*, *Rubus chamaemorus*, *Arctagrostis latifolia*, and *Polygonum bistorta* ssp. *plumosum*. The most common and abundant bryophytes and lichens include *Aulacomnium turgidum*, *Hylocomium splendens*, *Dicranum elongatum*, *Aulacomnium palustre*, and *Anastrophyllum minutum*; and *Dactylina arctica*, *Thamnolia vermicularis*, *Flavocetraria cucullata*, *Cladina rangiferina*, and *Peltigera aphthosa*, respectively.
A4347p	Arctic Nonacidic Tussock Tundra Alliance	The Arctic Nonacidic Tussock Tundra Alliance Proposed (A4347p) occurs in Upland physiography most commonly on the following geomorphic units: Alluvial-Marine Deposit; Frozen Upland Silt; and Thaw Basin, ice-rich center. The average elevation in this Alliance is 59 m (±69 m), and the slope gradient typically ranges between flat and gently sloping. This Alliance was commonly associated with the surface forms Nonpatterned and High-centered, Low-relief Polygons, but is also regularly associated with Mixed pits and polygons and High-centered, High-relief Polygons. Soils are poorly drained to moderately well drained, surface organic thickness typically ranges from thin to moderately thick, and coarse fragments are rare. Permafrost was common, with an average active layer thickness of 37 cm (±7 cm). Soil pH typically ranges from circumalkaline to alkaline, and the average electrical conductivity is 255 µS/cm (±210 µS/cm). The most common vegetation type is Tussock Tundra-Dryas. The vegetation is dominated by *Eriophorum vaginatum*, which forms conspicuous tussocks with a cover of whole tussocks of at least 5%. *Dryas integrifolia* and *Salix reticulata* are the most common and abundant dwarf shrubs. Other common plants include the shrubs *Cassiope tetragona*, *Salix richardsonii*, *Salix pulchra*, *Salix arctica*, and *Arctous rubra*, and the herbs *Carex bigelowii*, *Saussurea angustifolia*, *Eriophorum angustifolium*, *Arctagrostis latifolia*, *Poa arctica*, and *Polygonum viviparum*. The most common and abundant bryophytes and lichens include *Tomentypnum nitens*, *Hylocomium splendens*, *Aulacomnium turgidum*, *Ptilidium ciliare*, *Aulacomnium palustre*, *Dicranum elongatum*, *Rhytidium rugosum*, *Flavocetraria cucullata*, *F. nivalis*, *Thamnolia vermicularis*, *Dactylina arctica*, *Cetraria islandica*, respectively.
A4362	*Chamerion latifolium - Salix alaxensis* Arctic Floodplain Alliance	The *Chamerion latifolium - Salix alaxensis* Arctic Floodplain Alliance (A4362) occurs in Riverine physiography on Meander Coarse Active Channel Deposits and Braided Coarse Active Channel Deposits. The average elevation in this Alliance is 160 m (±159 m), and the slope gradient typically ranges between flat and nearly level. This Alliance was commonly associated with the surface forms Nonpatterned but is also regularly associated with Riverbed Cobbles or Boulders and Scour channels-ridges. Soils are somewhat excessively drained to excessively drained, surface organics are absent, or very thin and patchy, and coarse fragments are common, with an average top depth of 26 cm (±70 cm). Permafrost was absent or occurred at a depth >1.3 m. Soil pH is typically alkaline, and the average electrical conductivity is 80 µS/cm (±57 µS/cm). The most common vegetation types are Barrens, Partially Vegetated, and Seral Herbs. The vegetation is sparse (<10% vascular plant cover), and *Salix alaxensis*, *Chamerion latifolium*, *Eurybia sibirica*, and *Artemisia tilesii* are the most common plants. Other commonly occurring plants include the shrubs *Salix niphoclada*, *Dasiphora fruticosa*, and *Salix hastata*, and the herbs *Wilhelmsia physodes*, *Hedysarum alpinum*, *Arctagrostis latifolia*, *Festuca rubra*, *Trisetum spicatum*, and *Castilleja caudata*. Bryophytes and lichens are rare; the most common are *Racomitrium lanuginosum* and *Ceratodon purpureus*.
A4363p	*Salix alaxensis* River Bar Alliance	The *Salix alaxensis* River Bar Alliance Proposed (A4363p) occurs in Riverine physiography most commonly on the following geomorphic units: Meander Active Overbank Deposit, Braided Active Overbank Deposit, Delta Inactive Channel Deposit, Meander Coarse Active Channel Deposit, and Braided Coarse Active Channel Deposit. The average elevation in this Alliance is 123 m (±156 m), and the slope gradient typically ranges between flat and nearly level. This Alliance was commonly associated with the surface form Nonpatterned but is also regularly associated with Riverbed Cobbles or Boulders and Scour channels-ridges. Soils are well drained to somewhat excessively drained, surface organics are absent to very thin, and coarse fragments are common with an average top depth of 57 cm (±56 cm). Permafrost was absent or occurred at a depth >1.3 m. Soil pH is typically alkaline, and the average electrical conductivity is 208 µS/cm (±176 µS/cm). The most common vegetation types are Open Tall Willow, Closed Tall Willow, and Open Low Willow. The vegetation is dominated by *Salix alaxensis*, and *S. hastata*, *S. glauca*, and/or *S. richardsonii* are sometimes codominant in the low shrub layer. *Eurybia sibirica* and *Equisetum arvense* are the most common and abundant herbaceous species. Other common plants include the shrub *Arctous rubra*, and the herbs *Festuca rubra*, *Artemisia tilesii*, *Parnassia kotzebuei*, *Arctagrostis latifolia*, and *Astragalus alpinus*. Bryophytes are common, but are very patchy and occur at low cover, and lichens are generally absent. The most common bryophytes include *Sanionia uncinata*, *Brachythecium mildeanum*, *Leptobryum pyriforme*, *Campylium stellatum*, and *Bryum pseudotriquetrum*.
A4364p	*Salix glauca* River Bar & Dune Alliance	The *Salix glauca* River Bar & Dune Alliance Proposed (A4364p) occurs in Riverine and Upland physiography most commonly on the following geomorphic units: Eolian Inactive Sand Dune, Meander Inactive Overbank Deposit, and Braided Inactive Overbank Deposit. The average elevation in this Alliance is 68 m (±109 m), and the slope gradient typically ranges between flat and gently sloping. This Alliance was commonly associated with the surface forms Nonpatterned but is also regularly associated with Small Dunes and Wind Deflation. Soils are moderately well drained to somewhat excessively drained, surface organics are absent to thin, and coarse fragments are uncommon with an average top depth of 82 cm (±82 cm). Permafrost is uncommon in the upper 130 cm, but when it does occur the average active layer thickness is 70 cm (±29 cm). Soil pH is typically alkaline, and the average electrical conductivity is 94 µS/cm (±69 µS/cm). The vegetation is Open Low Willow. The vegetation is dominated by *Salix glauca*, and *S. richardsonii* or *S. pulchra* are sometimes codominant in the low shrub layer. *Astragalus alpinus* is the most common and abundant herbaceous plant. Other common plants include the shrubs *Arctous rubra*, *Dryas integrifolia*, and *Salix reticulata*, and the herbs *Equisetum arvense*, *Festuca rubra*, *Eurybia sibirica*, *Stellaria longipes*, *Bromus pumpellianus*, *Poa arctica*, *Trisetum spicatum*, and *Carex krausei*. The most common bryophytes are *Hylocomium splendens*, *Tomentypnum nitens*, *Aulacomnium palustre*, *Distichium capillaceum*, *Sanionia uncinata*, and *Rhytidium rugosum*; and *Flavocetraria cucullata*. Lichens are uncommon, but when they do occur the most frequently occuring species are *Flavocetraria cucullata* and *Peltigera aphthosa*.

Alliance Code	Alliance Title	Description
A4365p	*Salix alaxensis - Salix niphoclada* River Bar & Dune Alliance	The *Salix alaxensis - Salix niphoclada* River Bar & Dune Alliance Proposed (A4365p) occurs in Upland and Riverine physiography most commonly on the following geomorphic units: Eolian Active Sand Dune and Meander Fine Inactive Channel Deposit. The average elevation in this Alliance is 22 m (±31 m), and the slope gradient typically ranges between flat and strongly sloping. This Alliance was commonly associated with the surface form Small dunes but is also regularly associated with Nonpatterned and Wind Deflation. Soils are somewhat excessively drained to excessively drained, surface organics are absent or very thin and patchy, and coarse fragments are uncommon with an average top depth of 95 cm (±69 cm). Permafrost is absent in the upper 130 cm. Soil pH is typically alkaline, and the average electrical conductivity is 84 µS/cm (±158 µS/cm). The vegetation is Open Low Willow and Open Tall Willow. The vegetation is dominated by *Salix alaxensis*, or co-dominated by *S. alaxensis* and *S. niphoclada* in the low/tall shrub layer. The prostrate shrub *Arctous rubra* frequently occurs in the understory at low to moderate abundance. *Festuca rubra*, *Tanacetum bipinnatum* ssp. *bipinnatum*, and *Equisetum arvense* are the most common and abundant herbaceous plants. Other common plants include the shrub *Dryas integrifolia*, and the herbs *Equisetum variegatum*, *Bromus pumpellianus*, *Eurybia sibirica*, *Juncus arcticus*, *Astragalus alpinus*, *Carex maritima*, *Koeleria asiatica*, *Anemone parviflora*, *Chamerion latifolium*, and *Gentiana propinqua*. Bryophytes are uncommon and very patchy and occur at low cover, and lichens are generally absent. The most common bryophytes include *Bryum pseudotriquetrum*, *Ceratodon purpureus*, and *Leptobryum pyriforme*.
A4366p	Arctic Ombrotrophic Wet Low Shrublands Alliance	The Arctic Ombrotrophic Wet Low Shrublands Alliance Proposed (A4366p) occurs in Lowland physiography most commonly on the following geomorphic units: Lowland Loess, Lowland Retransported Deposit, and Meander Abandoned Overbank Deposit. The average elevation in this Alliance is 140 m (±235 m), and the slope gradient typically ranges between flat and gently sloping. This Alliance was commonly associated with the surface form Nonpatterned but is also regularly associated with Water tracks (non-incised drainages); Low-centered, Low-relief, High-density Polygons; and Undifferentiated mounds. Soils are very poorly drained to poorly drained, surface organic thickness typically ranges from moderately thick to very thick, and coarse fragments are rare, but when they do occur the top depth is 57 cm (±64 cm). Permafrost was common, with an average active layer thickness of 41 cm (±14 cm). Soil pH typically ranges from acidic to circumacidic, and the average electrical conductivity is 227 µS/cm (±272 µS/cm). The most common vegetation types include Open Low Willow-Sedge Shrub Tundra, Open Low Willow, and Open Low Shrub Birch-Willow. The vegetation is dominated by *Salix pulchra* or codominated by *S. pulchra* and *Betula nana* in the low shrub layer, and *Eriophorum angustifolium* and *Carex aquatilis* are the most common and abundant herbaceous species. Other common shrubs include *Salix richardsonii*, *S. fuscescens*, and *Andromeda polifolia*. *Salix reticulata*, *Ledum decumbens*, and *Vaccinium uliginosum* are commonly present at low abundance on moist microhighs. Other common herbs include *Poa arctica*, *Petasites frigidus*, *Saxifraga hirculus*, *Valeriana capitata*, *Polygonum viviparum*, and *Potentilla palustris*. Bryophytes are common and abundant, the most frequently occurring include *Tomentypnum nitens*, *Aulacomnium palustre*, *Hylocomium splendens*, *Aulacomnium turgidum*, *Sphagnum squarrosum*, *S. warnstorfii*, *S. girgensohnii*, and *S. fuscum*. Lichens are common but typically occur at low abundance on moist microhighs, the most common include *Peltigera aphthosa*, *Dactylina arctica*, and *Flavocetraria cucullata*.
A4367p	Arctic Minerotrophic Wet Low Shrublands Alliance	The Arctic Minerotrophic Wet Low Shrublands Alliance Proposed (A4367p) occurs in Riverine and Lacustrine physiography most commonly on the following geomorphic units: Delta Inactive Overbank Deposit; Meander Inactive Overbank Deposit; and Drained Lake Basin, ice-poor margin. The average elevation in this Alliance is 10 m (±10 m), and the slope gradient typically ranges between flat and gently sloping. This Alliance was commonly associated with the surface form Nonpatterned but is also regularly associated with Disjunct Polygon Rims and Low-centered, Low-relief, Low-density Polygons. Soils are very poorly drained to somewhat poorly drained, surface organic thickness typically ranges from very thin to moderately thick, and coarse fragments are rare, but when they do occur the top depth is 84 cm (±67 cm). Permafrost was common, with an average active layer thickness of 50 cm (±11 cm). Soil pH typically ranges from circumalkaline to alkaline, and the average electrical conductivity is 480 µS/cm (±438 µS/cm). The most common vegetation types include Open Low Willow-Sedge Shrub Tundra and Open Low Willow. The vegetation is dominated by *Salix richardsonii* in the low shrub layer, and *Eriophorum angustifolium* and *Carex aquatilis* are the most common and abundant herbaceous species. Other common plants include the shrubs *Salix reticulata*, *Dryas integrifolia*, and *Arctous rubra*, which typically occur on moist microhighs, and the herbs *Polygonum viviparum*, *Saxifraga hirculus*, and *Equisetum variegatum*. Bryophytes are common and abundant, the most frequently occurring include *Tomentypnum nitens*, *Campylium stellatum*, *Meesia triquetra*, *Hamatocaulis vernicosus*, *Limprichtia revolvens*, *Calliergon richardsonii*, and *Aulacomnium palustre*. Lichens are common but typically occur at low abundance on moist microhighs, the most common include *Dactylina arctica* and *Flavocetraria cucullata*.

The remaining 125 associations were assigned to the Arctic ecoregion. Of the Arctic associations, 50 were provisional associations ($n \geq 10$), including 25 shrubland and 25 herbaceous; and 75 were preliminary associations ($n = 4–9$), including 47 shrubland, 27 herbaceous, and one nonvascular. Of the plant community types, 45 were Boreal and 106 were Arctic. Of the Arctic plant community types, 64 were shrubland, 41 herbaceous, and 1 nonvascular. The results of the Partana analysis for preliminary and provisional associations group are presented by group in Suppl. material 3. The associations within Arctic Low Shrub Tundra had the highest within to between similarity ratio (Suppl. material 3A) and Arctic Herbaceous Tussock Tundra the lowest within to between cluster similarity ratio (Suppl. material 3B). In general, the associations within a group were most similar to other associations within the same alliance than they were to associations in another alliance; for example, the associations in the Arctic Ombrotrophic Wet Low Shrublands Alliance Proposed (Suppl. material 3C). Exceptions to this trend were rare and occurred in situations where associations in two alliances shared the same dominant species (Suppl. material 3D; e.g., *Salix alaxensis/Tanacetum bipinnatum* subsp. *bipinnatum*).

The low and tall willow, and tussock tundra associations and community types are listed in Table 3, and nested within the USNVC hierarchy. We identified seven provisional and one preliminary tussock tundra associations (Table 3). We classified 24 low and tall willow associations, including seven provisional and 17 preliminary, and 13 low and tall willow plant community types. The tussock tundra associations occurred within one division, one macrogroup, one proposed group, and four proposed alliances. The low and tall willow associations fell within two divisions, three macrogroups, and four existing and five proposed alliances.



Codes Explained

A4337: Arctic Acidic Low Willow Tundra All.
A4338: Arctic Nonacidic Low Willow Tundra All.
A4339: Arctic Dwarf Birch Low Shrub Tundra All.
A4344p: Arctic Acidic Shrub Tussock Tundra All.
A4345p: Arctic Nonacidic Shrub Tussock Tundra All.
A4346p: Arctic Acidic Tussock Tundra All.
A4347p: Arctic Nonacidic Tussock Tundra All.
A4362: *Chamerion latifolium* – *Salix alaxensis* Arctic Fldpn. All.
A4363p: *Salix alaxensis* River Bar All.
A4364p: *Salix glauca* River Bar & Dune All.
A4365p: *Salix alaxensis* – *Salix niphoclada* River Bar & Dune All.
A4366p: Arctic Ombrotrophic Wet Low Shrublands All.
A4367p: Arctic Minerotrophic Wet Low Shrublands All.

Figure 10. Vegetation structure cover stacked bar charts by low and tall willow and tussock tundra alliance, ELD Arctic association classification, Alaska.

A field guide to the tussock tundra and low and tall willow associations is provided in the supplemental online materials. The field guide includes (1) dichotomous keys for identifying all tussock tundra and low and tall willow associations in the field (Suppl. material 4); and (2) a summary of each association, including written descriptions, constancy/cover tables, photographs, distribution maps, and environmental data summary tables (Suppl. material 5). Additionally, a cross-reference table between the tussock tundra and low and tall willow associations and associations from existing published classifications is provided in Suppl. material 6.

Discussion

Divisions

The Arctic dataset presented here is divided into four USNVC divisions that represent broad combinations of dominant and diagnostic growth forms that reflect regional physiography distinctions, and gradients in soil moisture, hydrology, and salinity. The tussock tundra and low and tall willow associations fall within two of these divisions: Arctic Freshwater Marsh & Wet Meadow and Arctic Tundra & Barrens. These divisions differentiate Arctic tundra vegetation based on soil moisture and hydrology, and between xeric and mesic vegetation in uplands, and hydrophytic vegetation in wetlands. In some cases, this distinction is obvious, such as a low willow community on an active sand dune with dry, sandy soils versus a low willow community in a fen with wet, organic soils. However, in other cases the distinctions are less obvious. This is particularly so on the broad, flat Beaufort Coastal Plain (BCP) where soil moisture gradients are often very gradual and subtle, and vegetation types often co-occur within mosaics. To consistently distinguish between these two divisions, a set of quantitative and objective criteria are required. The criteria should rely on a set of readily made field observations and measurements. We have attempted to formulate this set of criteria in the key to associations (Suppl. material 4). We encourage the use of this key in the field and would appreciate feedback from field users. However, for transitional cases the key may be insufficient, and plots falling on the boundary between these two divisions should be assigned based on multivariate statistical analyses.

Macrogroups

Faber-Langendoen et al. (2020) present two macrogroups in the Arctic Tundra & Barrens Division: Arctic Dry-Moist

Tundra and Arctic Scree, Rock and Cliff Barrens. Tussock tundra was included under Arctic Dry-Moist Tundra in the Arctic Herbaceous Tundra Group and Arctic Tussock Sedge Tundra Alliance (A4343). In addition, Arctic inland dunes were recognized as distinct from Arctic coastal dunes, and the former was tentatively included in its own group, Arctic Inland Dune (G863), under the Arctic Coastal Scrub & Herb Vegetation Division and the North American Arctic Coastal Shore Macrogroup (M402).

The NMDS analysis of all plots in Arctic Tundra & Barrens (Figure 4) revealed two distinct groupings of plots corresponding to two existing macrogroups: Arctic Dry-Moist Tundra and Arctic Scree, Rock and Cliff Barrens. The high significance and strong fit of the surface organic thickness and thaw depth GAMs and the results of the silhouette analysis provides a measure of the strength of those vegetation-environment relationships.

In regions with continuous permafrost like Arctic Alaska, active layer thickness directly affects ground and surface water hydrology by impeding soil drainage. Areas of the landscape with deeper active layers and convex topography (e.g., dunes) are well drained, whereas areas with shallow active layers are typically paludified and poorly drained, particularly in flat and concave areas of the landscape. Active-layer thickness is largely affected by physiographic setting, soil texture, and surface organic thickness (Jorgenson et al. 2015). For instance, the GAMs results indicated that a gradient in thaw depth and surface organic thickness is present across the macrogroups in this division. This reflects a gradient in disturbance history from sites with regular disturbance (e.g., wind deflation on dunes and fluvial erosion on river bars) to stable sites, such as tussock tundra, which experience very little disturbance for extended periods (decades to centuries). Thus, the results of the NMDS analysis indicate that the two existing macrogroups are distinct both floristically, based on moderate sets of diagnostic plant species and growth forms, and environmentally, based on differences in surficial geology, hydrology, and disturbance regimes.

Faber-Langendoen et al. (2020) recognized that Arctic inland dunes are distinct from coastal dunes and should therefore be placed in the context of tundra. Arctic inland dunes are considered rare ecosystems in Alaska, provide habitat for several rare and sensitive plant taxa, such as *Mertensia drummondii*, and are of high importance for conservation (Cortés-Burns et al. 2009; Boggs et al. 2019; Flagstad et al. 2019; ACCS 2021). However, a complete discussion regarding the placement of Arctic inland dunes within the USNVC hierarchy was beyond the scope of the 2017 Alaska USNVC working session. In lieu of a comprehensive discussion on Arctic inland dunes, the working group tentatively placed them near Arctic coastal dunes within Arctic Coastal Scrub & Herb Vegetation/ North American Arctic Coastal Shore.

Arctic inland dunes are unique from coastal dunes both floristically and environmentally. For instance, USNVC (2019) describes Arctic Coastal Scrub & Herb Vegetation as being found "on North American Arctic coastline beaches, beach dunes, and stabilized vegetated sand or cobble deposits, with *Leymus mollis* grasslands and *Empetrum nigrum* dwarf-shrublands, as well as on sea cliffs, rocky headlands, and cobble beaches of the Arctic coastline….". Similarly, North American Arctic Coastal Shore is described as found "on North American Arctic coastline beaches, beach dunes, stabilized sand, cobble deposits, on sea cliffs, rocky headlands, and cobble beaches....". Coastal dunes form by eolian transport of beach sands, and experience regular salt spray and periodic inundation by saltwater from storm surges. In contrast, Arctic inland dunes are found most commonly along rivers (Figure 11), in recently (< 50 years ago) drained lake basins in the sand sheet region of the BCP (Carter 1981) between the Colville and Meade Rivers, and in small patches on lake and river bluffs and ancient moraines (Boggs et al. 2019). Inland dunes form by the accumulation of eolian alluvial and palustrine sands and are never influenced by saltwater. The frequent proximity of inland dunes to early successional river bars results in high similarity of plant species assemblages in the two environments (Figure 4D) compared to coastal dune vegetation (Figure 12, Table 5). Additionally, low and tall willows, most commonly *Salix alaxensis* and *S. niphoclada*, frequently occur on inland dunes and are not found on coastal dunes. Therefore, we propose here that Arctic inland dunes be placed in the Arctic Tundra & Barrens Division along with early successional riverine vegetation under the Arctic Scree, Rock & Cliff Barrens Macrogroup.

Faber-Langendoen et al. (2020) moved Arctic riparian tall willow from Arctic Tundra & Barrens /Arctic Dry-Moist Tundra to Arctic & Boreal Freshwater Marsh, Wet Meadow & Shrubland/Arctic Freshwater Marsh, Wet Meadow & Shrubland. We have shown in Figure 5A that the riparian low and tall willow vegetation on river bars and lower floodplain positions is distinct from the wet willow vegetation. We also showed that riparian low and tall willow vegetation is more similar to willow shrublands on dunes, and thus we have proposed that riparian low and tall willow vegetation be classified into the Arctic Scree, Rock, and Cliff Barrens Macrogroup. Soils along rivers in the Arctic generally have deep active layers, thin surface organic layers, and coarser textures, and thus have a deeper rooting zone and are better drained than soils in lowlands (Schickhoff et al. 2002; Liljedahl et al. 2020). In addition, riverine willow communities are typically flooded for only a short duration early in the growing season when the active layer is still frozen, whereas the soils in lowland willow communities are continuously flooded or saturated throughout the growing season. The differences in thaw depth, flooding frequency, and duration of flooding result in very different vegetation structures (tall shrubs in riverine areas) and understory species assemblages (predominance of hydrophytes in lowlands). Additionally, shrub canopy height and volume in the Alaskan Arctic have been shown to be positively correlated with the frequency of overbank flooding, active layer thickness, and soil drainage (Swanson 2015). If the above proposed changes are accepted then we recommend

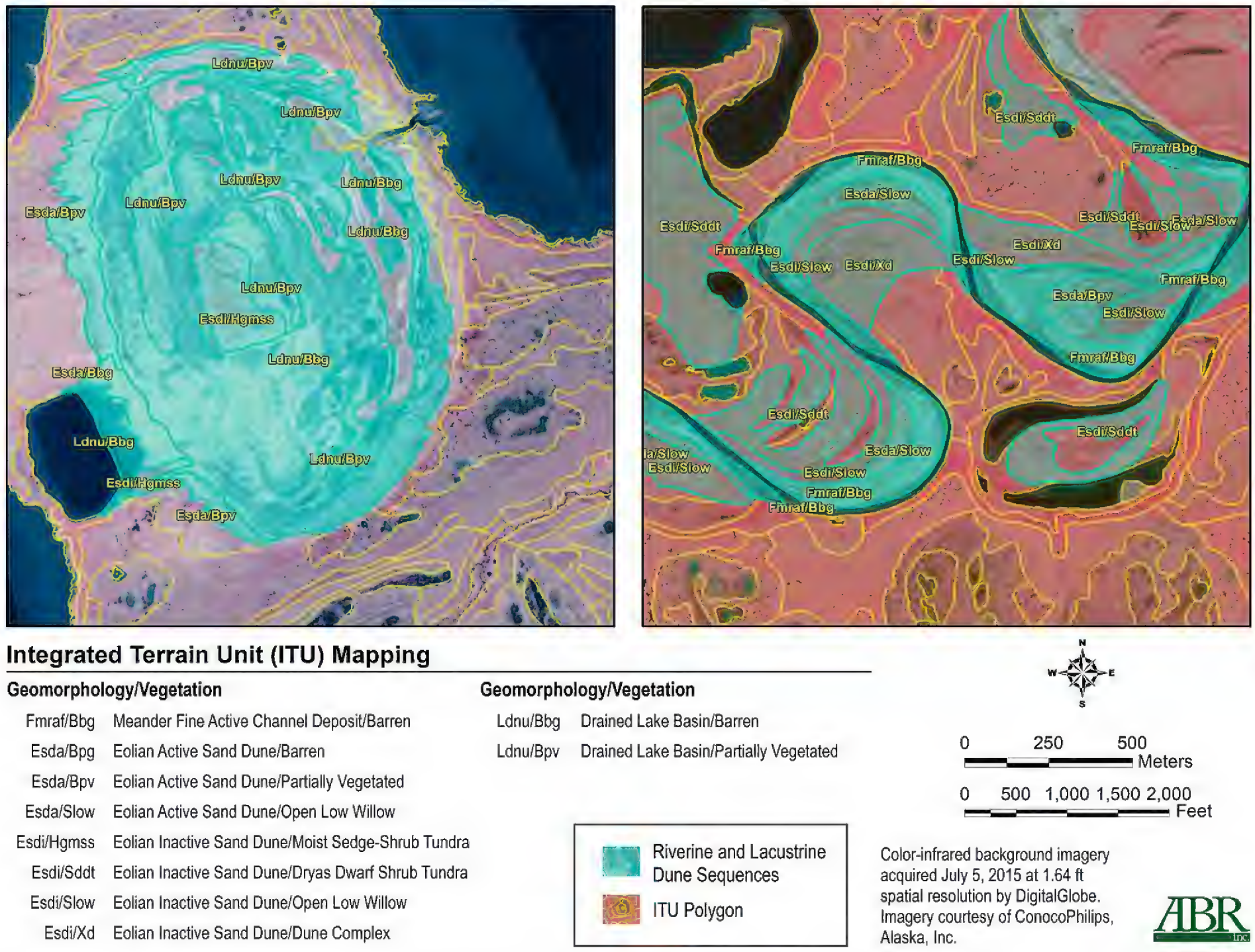


Figure 11. Examples of inland dune landscapes in a recently drained lake basin from the sand sheet region of the Beaufort Coastal Plain (left panel) and on the floodplain of Judy Creek (right) showing the Integrated Terrain Unit (ITU) map unit polygons and geomorphic unit and vegetation class assignments from Wells et al. (2020) over high-resolution satellite imagery from July 2018. The latitude and longitude (WGS84) of the centroids of each panel are as follows: Left panel 70.336953 -152.310269; Right panel 70.119314 -152.248539, ELD Arctic association classification, Alaska.

1) broadening the concept of Arctic Scree, Rock & Cliff Barrens to include barrens and early successional vegetation on river bars, lower floodplains, and inland dunes, and 2) a name change from Arctic Scree, Rock & Cliff Barrens to Arctic Scree, Rock, Cliff & River Bar Barrens.

Groups

Tussock tundra, as presently classified in Faber-Langendoen et al. (2020) as a single alliance under the Arctic Herbaceous Tundra Group, does not allow for distinctions between tussock tundra and herbaceous nontussock tundra at the group level. Additionally, the classification of tussock tundra in Faber-Langendoen (2020) only distinguishes between shrub (i.e., tussock tundra with a significant shrub component) and herbaceous tussock tundra or acidic and nonacidic tussock tundra at the association level, but we have shown that these are important higher-level distinctions, ones that are also useful for vegetation mapping. Figures 8, 9, and 10 show a clear distinction at the group level between tussock tundra and nontussock tundra, and between shrub tussock tundra and herbaceous tussock tundra in both floristic composition and vegetation structure. Thus, we have proposed that the Arctic Herbaceous Tundra Group gets split into tussock and nontussock tundra groups and proposed the following group names: Arctic Herbaceous Tussock Tundra Proposed and Arctic Herbaceous Nontussock Tundra Proposed. The later proposed group is similar in concept to the previously accepted North American Arctic & Subarctic Tussock Tundra Group (G371), which was aggregated into Arctic Herbaceous Tundra by Faber-Langendoen et al. (2020).

Faber-Langendoen et al. (2020) moved Arctic riparian tall willow from Arctic Tundra & Barrens /Arctic Dry-Moist Tundra to Arctic & Boreal Freshwater Marsh, Wet Meadow & Shrubland /Arctic Freshwater Marsh, Wet Meadow & Shrubland, and a new group was proposed: North American Arctic Tall Willow Wet Shrubland Group

Table 5. Constancy/cover tables for coastal dunes and beaches, and inland dunes and floodplains showing the top 20 most common vascular taxa in each physiographic setting, ELD Arctic plant association classification, Alaska. *: Salt-tolerant.

Physiographic Setting	Lifeform	Scientific Name	Avg. Cover (%)	Constancy (%)
Coastal Dunes and Beaches	Deciduous Shrubs	*Salix ovalifolia**	11.5	65
	Grasses	*Leymus mollis* subsp. *mollis**	10.1	44
	Grasses	*Dupontia fisheri**	8.1	37
	Forbs	*Stellaria humifusa**	1.9	35
	Sedges	*Carex ursina**	6.9	33
	Grasses	*Puccinellia phryganodes**	6.6	33
	Sedges	*Carex subspathacea**	18.9	33
	Grasses	*Poa arctica*	1.7	30
	Sedges	*Eriophorum angustifolium*	5	23
	Forbs	*Lathyrus japonicus* var. *maritimus**	9.7	21
	Forbs	*Artemisia tilesii*	1.1	19
	Forbs	*Cochlearia officinalis**	0.4	16
	Forbs	*Honckenya peploides**	2.3	16
	Forbs	*Sedum rosea* subsp. *integrifolium*	2.3	16
	Forbs	*Armeria maritima* subsp. *arctica*	0.4	14
	Grasses	*Deschampsia cespitosa*	4.1	14
	Forbs	*Cerastium beeringianum*	0.8	12
	Forbs	*Potentilla pulchella*	1.5	12
	Forbs	*Primula borealis*	1	12
	Forbs	*Astragalus alpinus*	3	12
Inland Dunes and River Bars	Grasses	*Festuca rubra*	2.1	62
	Deciduous Shrubs	*Salix alaxensis*	20.4	58
	Ferns and allies	*Equisetum arvense*	6.2	56
	Evergreen Shrubs	*Dryas integrifolia*	18.1	49
	Forbs	*Eurybia sibirica*	2.3	48
	Forbs	*Astragalus alpinus*	3	48
	Deciduous Shrubs	*Salix glauca*	10	42
	Deciduous Shrubs	*Arctous rubra*	8.2	40
	Forbs	*Polygonum viviparum*	0.4	38
	Deciduous Shrubs	*Salix richardsonii*	12.4	38
	Grasses	*Poa arctica*	1	36
	Deciduous Shrubs	*Salix reticulata*	5.9	35
	Grasses	*Arctagrostis latifolia*	1.8	34
	Grasses	*Trisetum spicatum*	0.4	32
	Grasses	*Bromus pumpellianus*	2.3	30
	Forbs	*Artemisia tilesii*	2.7	30
	Ferns and allies	*Equisetum variegatum*	3.6	28
	Forbs	*Tanacetum bipinnatum* subsp. *bipinnatum*	2.6	28
	Forbs	*Chamerion latifolium*	2.7	25
	Forbs	*Anemone parviflora*	1.5	24

(G368). We demonstrated above that low and tall willow vegetation on river bars and lower floodplains and on inland dunes are more similar to each other than to coastal dune and wet willow vegetation, and have proposed that low and tall willow vegetation on river bars and inland dunes be classified into Arctic Scree, Rock, and Cliff Barrens. We further propose that riparian low and tall willow vegetation on river bars and lower floodplain positions and on inland dunes be placed with in the Arctic Gravel Floodplain Vegetation Group. This is supported by Figures 4D and 5A which show clear distinctions in physiography and vegetation structure between Arctic Dry-Moist Tundra and Arctic Scree, Rock, & Cliff Barrens, and their component groups. In addition to placing all early successional riparian vegetation and inland dune vegetation together, the proposed change would also place all Arctic vegetation dominated by *Salix alaxensis* in the same group.

We also recommend that future USNVC revisions include: 1) broadening the concept of Arctic Gravel Floodplain Vegetation slightly to include inland dunes, 2) changing the title of this group to Arctic River Bar & Inland Dune Vegetation, and 3) reevaluating the concept of G368.

Alliances

Low and tall willow

Arctic low and tall willow vegetation fits in two divisions that differentiate between dry-moist tundra (Arctic Tundra and Barrens) and wet tundra (Arctic & Boreal Freshwater Marsh, Wet Meadow & Shrubland). Dry and moist low and tall willow vegetation falls within two existing macrogroups and three existing groups (Figure

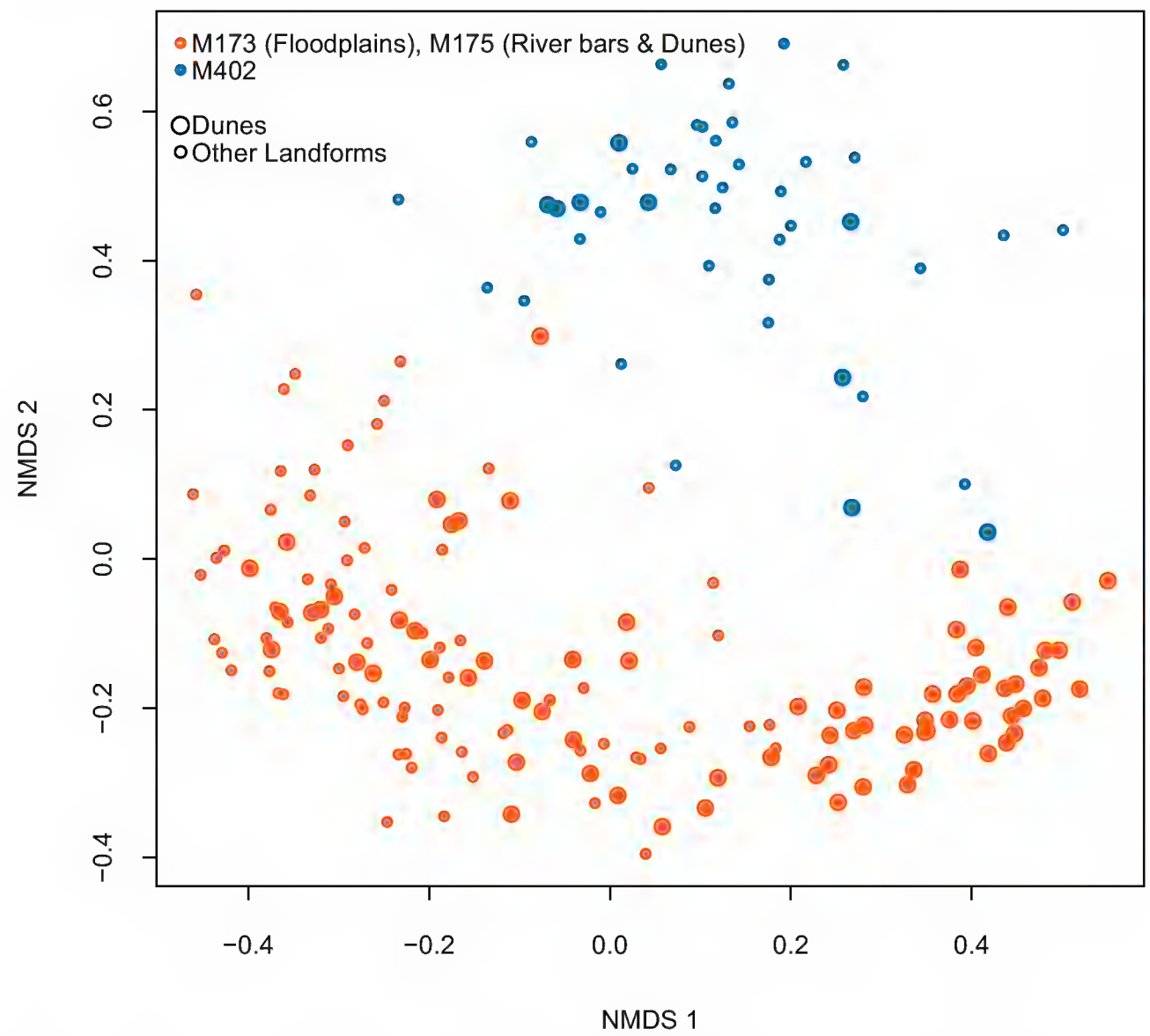


Figure 12. Non-metric Multidimensional Scaling (NMDS) ordination of Arctic plots in Macrogroups Arctic Dry-Moist Tundra (M173, floodplain plots only), Arctic Scree, Rock and Cliff Barrens (M175, river bar and dune plots only), and Arctic Coastal Scrub and Herb Vegetation (M402). The ordination illustrates the distinct plant species composition on coastal dunes and beaches (M402) versus inland dunes, riverbars, and floodplains (M173 and M175), ELD Arctic association classification, Alaska.

4D and 5A, Table 3). The low and tall willow vegetation in Arctic Dry-Moist Tundra fits cleanly into three existing alliances based on the codominance of dwarf birch with willows (Arctic Dwarf Birch Low Shrub Tundra) and soil pH (Arctic Acidic Low Willow Tundra and Arctic Nonacidic Low Willow Tundra; Figure 5B, Figure 6). This classification of low and tall willow vegetation also fits well with an existing physiognomic-floristic classification for Alaska (Viereck et al. 1992), which differentiates dwarf birch-willow vegetation types and with the current understanding of acidic and nonacidic tundra. Descriptions and representative photos for each low and tall willow alliance are provided in Table 4 and Figure 7.

Faber-Langendoen et al. (2020) classified one alliance under Arctic Scree, Rock, and Cliff Barrens, and two alliances in North American Arctic Wet Shrubland under the macrogroup Arctic Freshwater Marsh, Wet Meadow & Shrubland. We have proposed new alliances and changes to existing alliances for these macrogroups (Table 3). The low and tall willow vegetation in Arctic Freshwater Marsh, Wet Meadow & Shrubland fall under the North American Arctic Wet Shrubland Group and are distinguished by physiography and water chemistry into ombrotrophic wetlands (Arctic Ombrotrophic Wet Low Shrublands Alliance Proposed) in lowlands, and minerotrophic wetlands (Arctic Minerotrophic Wet Low Shrublands Alliance Proposed) on upper floodplain positions and in recently drained lake basins (Figure 5C, Figure 6). The physiographic and water chemistry differences reflect the different landscape-development processes in these environments and produce predictable differences in species composition, vegetation productivity, and soil properties. For instance, vegetation on upper floodplains is more productive than in lowlands because regular, but seasonal, flooding and sedimentation on floodplains provide a steady source of nutrients, while lowlands are often nutrient limited (Shaver and Chapin 1991; Schickhoff et al. 2002). Similarly, drained lakes in the Arctic have higher soil fertility and pH in the early and middle stages of lake basin development than in the later stages (Loiko et al. 2020). In parallel with this shift in soil properties is a shift from ice-poor permafrost and nonpatterned microtopography to ice-rich permafrost with well-developed ice-wedge polygons (Jorgenson and Shur 2007). In the early stage of lake basin development, the hydrology is controlled by groundwater (minerotrophic system) and the lack of ice-wedge polygons promotes the exchange of nutrients across the basin. In later stages, the hydrology is precipitation-controlled, and the ice-wedge polygon rims limit lateral movement of soil water and nutrients. The proposed classification of alliances in Arctic Freshwater Marsh, Wet Meadow & Shrubland/ North American Arctic Wet Shrubland presented here characterizes these landscape-vegetation-hydrology relationships and follows established concepts used to

categorize wetlands based on the predominant sources of water and nutrients (Rubec 2018).

We proposed above to change the titles of the two existing alliances under the North American Arctic Wet Shrubland Group, *Betula nana - Ericaceous* Arctic Wet Shrubland Alliance and Arctic Willow Wet Shrubland Alliance, to correspond to our proposed Arctic Ombrotrophic Wet Low Shrublands Alliance and Arctic Minerotrophic Wet Low Shrublands Alliance, respectively. The proposed title changes would allow for a wider variety of shrub vegetation in the *Betula nana - Ericaceous* Arctic Wet Shrubland Alliance that is characteristic of ombrotrophic wetlands. The proposed change would also tighten the concept of the Arctic Willow Wet Shrubland Alliance to include only minerotrophic shrub wetlands. Differentiating these two alliances based on site chemistry would be consistent with how alliances in other groups have been differentiated based on soil pH (e.g., acidic vs. nonacidic low willow alliances in the Arctic Low Shrub Group). An alternative approach could be to leave the *Betula nana - Ericaceous* Arctic Wet Shrubland Alliance as is, and then split the Arctic Willow Wet Shrubland Alliance into ombrotrophic and minerotrophic alliances.

The remaining low and tall willow vegetation in Arctic Tundra & Barrens falls under the Arctic Scree, Rock & Cliff Barrens Macrogroup and Arctic Gravel Floodplain Vegetation Group. In this group there is one existing alliance: *Chamerion latifolium - Salix alaxensis* Arctic Floodplain alliance. We have proposed three new alliances (Table 3): *Salix alaxensis* River Bar Alliance Proposed, *Salix glauca* River Bar & Dune Alliance Proposed, and *Salix alaxensis - Salix niphoclada* River Bar & Dune Alliance Proposed. The vegetation in these alliances is related along a successional sequence from barren and partially vegetated river bars, to early successional low and tall willow communities on river bars and lower floodplain positions; and from low and tall willow on active sand dunes to low willow on inactive sand dunes (Suppl. material 7). The relationship between plant species composition and geomorphic surface is illustrated in Figure 5D, which shows *Chamerion latifolium - Salix alaxensis* Arctic Floodplain and *Salix alaxensis* River Bar Proposed Alliances occurring predominantly on active channel and overbank deposits. These two alliances occupy the lowest river bar and floodplain positions and are therefore subjected to the most frequent and intense flooding, sedimentation, and erosion. Alliance *Salix alaxensis - Salix niphoclada* River Bar & Dune Proposed occurs most commonly on active sand dunes and occasionally on active or inactive channel or bar deposits. Lastly, the *Salix glauca* River Bar & Dune Alliance occurs on a variety of geomorphic surfaces but is found most commonly on inactive (partially stabilized) sand dunes. The proposed classification of alliances in Arctic Scree, Rock & Cliff Barrens represent distinct stages in vegetation succession along river bar-floodplain-dune toposequences. The proposed alliances also correspond to distinctive geomorphic surfaces that experience a unique suite of disturbance processes and represent characteristic phases of succession and landscape development.

Tussock tundra

We have proposed here that tussock tundra be moved from the alliance level under Arctic Tundra & Barrens/ Arctic Dry-Moist Tundra, to its own group, and we have proposed four tussock tundra alliances (Table 3). Figure 10 illustrates the clear distinction in shrub cover between the shrub tussock and herbaceous tussock alliances, and Figure 6 displays the differences in pH between acidic and nonacidic alliances. However, the GAM of soil pH in Figure 9 suggests that the soil pH gradient is more important in distinguishing between the tussock tundra alliances than it is for the shrub tussock tundra alliances.

Our proposed classification of tussock tundra alliances based on vegetation physiognomy (shrub tussock tundra vs. tussock tundra) fits well with Viereck et al. (1992), a comprehensive, widely accepted, statewide vegetation classification system based on a physiognomic-floristic approach, which differentiates between Open Low Mixed Shrub-Sedge Tussock Tundra and Tussock Tundra, based on a threshold of ≥ 25% shrub cover in the former. Our proposed tussock tundra alliance classification is also based on soil pH (acidic vs. nonacidic; Figure 6), which is a distinction that is well understood and accepted for Arctic tundra in Alaska (Walker et al. 1982, 1998, 2001, 2014) and clearly illustrated in Figure 6. Distinguishing tussock tundra at the group level, and further distinguishing alliances based on vegetation structure and soil pH, allows for those classes to be included in vegetation maps at circumarctic and regional scales. Additionally, the alliances can be aggregated in various ways to best fit future mapping objectives. For instance, if the purpose of a vegetation mapping effort is to distinguish between different types of tussock tundra based on soil pH (such as tundra sensitivity to seismic surveys of Raynolds et al. 2020), then the alliances can be aggregated into acidic and nonacidic tussock tundra classes in the map legend. Whereas if the objective of the mapping is to distinguish between vegetation types based on vegetation structure (such as the wildlife habitat mapping of Macander et al. 2020), then the alliances can be aggregated into shrub and herbaceous tussock tundra classes in the map legend. Descriptions and representative photos for each tussock tundra alliance are provided in Table 4 and Figure 7.

Associations

Low and tall willow

Associations in the Arctic Ombrotrophic Wet Low Shrublands Alliance Proposed are dominated by *Salix pulchra* or co-dominated by *S. pulchra* and *Betula nana*. The herbaceous component is dominated by the hydrophytic sedges *Carex aquatilis* and *Eriophorum angustifolium*, a variety of hydrophytic forbs (e.g., *Comarum palustre*), and bryophytes indicative of bogs (e.g., *Sphagnum*). In contrast, the Arctic Minerotrophic Wet Low Shrublands Alliance Proposed is characterized by *Salix richardsonii* and an

herbaceous component similar to Arctic Ombrotrophic Wet Low Shrublands. The bryophyte communities in these two associations include species characteristic of fens, including *Campylium stellatum*, *Limprichtia revolvens*, and *Calliergon richardsonii*.

Associations in the Arctic Dwarf Birch Low Shrub Tundra Alliance are differentiated from other closely related alliances (Arctic Acidic Low Willow Tundra and Arctic Nonacidic Low Willow Tundra) by the co-dominance of *Betula nana* with low willows. The associations within Arctic Dwarf Birch Low Shrub Tundra are distinguished first by the co-dominant willow species, either *Salix pulchra* or *S. glauca*, and secondarily based on the predominance of dwarf ericaceous shrubs (*Vaccinium vitis-idaea*) or forbs (*Petasites frigidus*).

Associations in the alliances Arctic Acidic Low Willow Tundra and Arctic Nonacidic Low Willow Tundra are distinguished first by the dominant willow species. In Arctic Acidic Low Willow Tundra, *Salix pulchra* is the dominant willow while in Arctic Nonacidic Low Willow Tundra, *S. glauca* or *S. richardsonii* are the dominant willows. Walker et al. (2001) list *S. pulchra* and *S. glauca* as commonly occurring in moist acidic and nonacidic tundra, respectively. Associations in Arctic Acidic Low Willow Tundra are distinguished by total shrub cover and the proportion of total cover of forbs relative to graminoid cover. The associations are further differentiated by the constancy and cover of forbs (*Equisetum arvense* or *Petasites frigidus*) or graminoid species (*Carex bigelowii*). Similarly, the associations in Arctic Nonacidic Low Willow Tundra are differentiated first by total shrub cover, most importantly the prostrate shrubs *Arctostaphylos rubra* or *Dryas integrifolia*, and the proportion of total cover of forbs relative to graminoid cover. Many of the constant and characteristic species in the Arctic Nonacidic Low Willow Tundra associations (Table 3, Suppl. material 5) are listed by Walker et al. (2001) as common and abundant in moist nonacidic tundra (e.g., *D. integrifolia*, *Lupinus arcticus*, *and Tomenthypnum nitens*).

The associations in the Arctic Scree, Rock & Cliff Barrens Macrogroup and Arctic Gravel Floodplain Vegetation Group were assigned to alliances based on the dominant or co-dominant willow species and geomorphic units. For instance, associations in the *Salix alaxensis* River Bar Alliance Proposed are dominated by *Salix alaxensis* or co-dominated by *S. alaxensis* and other willows and occur on river bars and lower floodplain positions. The associations within the alliances are differentiated by understory species indicative of the characteristic geomorphic units, and the related edaphic conditions and disturbance regimes. Examples of this are the *Salix alaxensis/Eurybia sibirica* Association, which typically occurs on river bars with coarse-textured sandy and rocky soils, and the *Salix alaxensis/Equisetum arvense* Association, which occurs most commonly on inactive channel and active overbank deposits with fine-textured soils. The associations in *Salix alaxensis* River Bar Alliance Proposed are related to those in the *Chamerion latifolium - Salix alaxensis* Arctic Floodplain Alliance along a continuum in vegetation succession from early successional river bars to later successional tall willow communities on upper floodplain positions.

Tussock tundra

The associations in the two acidic tussock tundra alliances, Arctic Acidic Shrub Tussock Tundra and Arctic Acidic Tussock Tundra, are characterized by a strong ericaceous shrub component (Suppl. material 5). This is illustrated in Figure 9B in which PESC is predicted to increase from the upper left to lower right corners of the ordination, paralleling the predicted decrease in pH (Figure 9A) and corresponding to the nonacidic and acidic tussock tundra alliances, respectively. *Ericaceous* shrubs have a propensity for acidic soils, and they excrete organic acids in a positive feedback loop that helps maintain soil acidity. The associations in the acidic tussock tundra alliances also had lower vascular species richness (avg. 14.6 ± 1.9) than the associations in the nonacidic tussock tundra alliances (A4345 and A4347, avg. 17.7 ± 3.3). A similar trend in species richness was observed by Walker et al. (2001) for moist acidic and nonacidic tundra in the Alaskan Arctic. In addition, soil pH has been found to be significantly and positively correlated with species richness in tussock tundra in the Alaskan Arctic (Gough et al. 2000).

The acidic and nonacidic tussock tundra alliances also share similarities in species composition with the moist acidic and nonacidic tundra described by Walker et al. (2001). For instance, the moist acidic tussock tundra associations are dominated by *Eriophorum vaginatum*, *Betula nana*, and *Ledum palustre* subsp. *decumbens*; *Rubus chamaemorus* and *Vaccinium vitis-idaea* occur at low to moderate abundance; and the bryophytes are dominated by a variety of *Sphagnum* species, most notably *S. girgensohnii* and *S. warnstorfii*. In contrast, the non-acidic tussock tundra associations are characterized by a predominance of *Eriophorum vaginatum*, *Dryas integrifolia*, and *Salix reticulata*; the graminoids *Arctagrostis latifolia* and *Carex bigelowii* occur at low to moderate abundance; and there is a high cover of the moss *Tomenthypnum nitens*.

The Partana analysis indicated that the low and tall willow and tussock tundra associations were distinct from other associations in the same group, and in most cases were most similar to associations within the same alliance (Suppl. material 3). One exception is *Eriophorum vaginatum/Ledum palustre* subsp. *decumbens–Vaccinium vitis-idaea* from the proposed Arctic Acidic Tussock Tundra Alliance which is most similar to *Ledum palustre* subsp. *decumbens/Eriophorum vaginatum* from the proposed Acidic Shrub Tussock Tundra Alliance (Suppl. material 3B). The two associations have *Ledum palustre* subsp. *decumbens* in common, which is a characteristic species in the former and dominant species in the latter, and both are in acidic tussock tundra alliances. The results indicate that these two associations could be merged, or that the dwarf shrub cover threshold used to distinguish between shrub (≥35%) and herbaceous (<35%) tussock tundra may need to be reevaluated (Suppl. material 4).

For instance, the split between shrub and herbaceous tussock tundra could be based solely on the combined cover of low and tall shrubs, or the combined cover of dwarf, low, and tall shrub could be increased. Another exception is *Salix alaxensis/Tanacetum bipinnatum* subsp. *bipinnatum*, which is most similar to an association in the *Salix alaxensis* River Bar Alliance Proposed than it is to *Salix niphoclada–Salix alaxensis/Arctous rubra*, the other association within *Salix alaxensis - Salix niphoclada* River Bar & Dune Alliance Proposed (Suppl. material 3D). This suggests that *Salix alaxensis/Tanacetum bipinnatum* subsp. *bipinnatum* may fit better in the *Salix alaxensis* River Bar Proposed Alliance and could potentially be merged with *Salix alaxensis/Eurybia sibirica*. However, *Salix niphoclada–Salix alaxensis/Arctous rubra* is most similar to *Salix alaxensis/Tanacetum bipinnatum* subsp. *bipinnatum* which, combined with the results of the ordination and silhouette analyses presented in Figure 5D and Suppl. material 2E, indicates that separating these two associations into their own alliance is reasonable. Future work on the low and tall willow and tussock tundra alliances and associations should focus on gathering additional relevés from existing datasets, for instance AVA-AK (Walker et al. 2016a), and new field work to increase the overall sample size and test the fidelity of the proposed alliances and associations presented here.

Conclusion

The USNVC workshop held in November 2017 in Anchorage, Alaska resulted in significant progress towards the classification of macrogroups, groups, and alliances for Alaska (Faber-Langendoen et al. 2020). However, the USNVC in Alaska is open to ongoing improvement through a structured peer review process. The results presented here are an attempt to fit the tussock tundra and low and tall willow associations from the peer reviewed ELD northwestern Alaskan Arctic association classification into the IVC and USNVC. In some cases, the associations fit seamlessly within these classifications. This was true for the alliances and associations in the Arctic Low Shrub Tundra Group. In other cases, for instance the North American Arctic Wet Shrubland Group (G830), preliminary alliances had been defined, and we have proposed a refinement to those alliances here. In still other cases, we have proposed a new group and a broader concept of an existing group using a data-driven approach. These proposals (1) address questions that remained unanswered in Faber-Langendoen et al. (2020), as is the case with inland dune vegetation; (2) provide a classification that reflects the need for mappable classes (cf. Raynolds et al. 2019) at the group and alliance levels of the USNVC (e.g., Tussock Tundra vs. Shrub Tussock Tundra), and/or (3) fit the classification of tussock tundra alliances within the well-established concepts of moist acidic and nonacidic tundra (Walker et al. 2001, 2018). A list of our proposed changes is provided in Table 6.

Table 6. List of proposed changes to the classification of Arctic low and tall willow and tussock tundra vegetation, ELD Arctic plant association classification, Alaska.

ID	Proposed Change
1	Broaden the concept of Arctic Gravel Floodplain Vegetation Group (G616) slightly to include inland dunes and change the Group title to Arctic River Bar & Inland Dune Vegetation.
2	Reevaluate the concept for the North American Arctic Tall Willow Wet Shrubland Group (G368) at the next USNVC working group meeting in Alaska.
3	Split the Arctic Herbaceous Tundra Group into tussock and nontussock tundra Groups with the following titles: Arctic Herbaceous Tussock Tundra (G899p) and Arctic Herbaceous Nontussock Tundra (G898p), respectively.
4	Title changes as follows: 1) *Betula nana* - Ericaceous Arctic Wet Shrubland Alliance to Arctic Ombrotrophic Wet Low Shrublands Alliance, and 2) Arctic Willow Wet Shrubland Alliance changes to Arctic Minerotrophic Wet Low Shrublands Alliance.
5	Add seven new Alliances as detailed in Table 4.

The work presented here assesses groups and alliances with robust analyses using data from northwestern Arctic Alaska, and then outlines a path forward for classifying associations. This work is part of a larger effort to build upon the existing IVC and USNVC with a refined classification of groups and alliances, and a comprehensive classification of associations for Arctic Alaska. To accomplish this goal, in the future we anticipate merging the ELD data with the AVPD (ACCS 2019) and pooling the combined dataset with the AVA-AK (Walker et al. 2016a) data to broaden and further refine the analysis and classification presented here. Until this broader classification effort can be accomplished the results of this study can be used in several ways to advance future classification efforts. First, this manuscript can be referred to in future Alaska USNVC workshops to help refine the classification of macrogroups, groups, and alliances. Secondly, the methods describe a data-driven approach to fitting associations into the IVC and USNVC hierarchy using ordination analysis and GAMs that could be used for future classification efforts. Thirdly, the key to low and tall willow and tussock tundra associations, and the related association descriptions, can be used by researchers in the field to classify these vegetation types at all levels of the USNVC hierarchy. We encourage the use of these tools in the field and welcome feedback to continue to refine the classification.

Data availability

The data will be made available on the Alaska Vegetation Plots Database (https://akveg.uaa.alaska.edu/). The Alaska Vegetation Plots Database is an open access repository of plot data from spatially explicit, extensive vegetation studies and ecological monitoring surveys. The Alaska Vegetation Plots Database enables users to analyze vegetation plot data from multiple projects conducted across Alaska according to a common schema and taxonomic standard, which are critical prerequisites to regional ecological analyses and mapping.

Author contributions

A.F.W. planned the research and led the writing, data compilation and analysis, and figure and table preparation; C.S.S. contributed to the data compilation, performed the climate analysis, led the writing of the study area section, and contributed to the preparation of the online resources; S.L.I. contributed to the data compilation, methods section text, and preparation of the online resources; R.W.M. contributed to the data compilation and preparation of the online resources; D.D. prepared the map figures; while all authors critically reviewed the manuscript.

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Supplementary material

Supplementary material 1
Data compilation methods for the Ecological Land Survey Legacy Database (ELD). PDF
Link: https://doi.org/10.3897/VCS.65469.suppl1

Supplementary material 2
Silhouette diagrams for levels of the U.S. National Vegetation Classification for the Arctic from Division to Alliance, Ecological Land Survey Legacy Database (ELD) Arctic Plant Association Classification, Alaska. PDF
Link: https://doi.org/10.3897/VCS.65469.suppl2

Supplementary material 3
Results of the Partana analysis for Arctic low and tall willow and tussock tundra Associations by Group, Ecological Land Survey Legacy Database (ELD) Arctic Plant Association Classification, Alaska. PDF
Link: https://doi.org/10.3897/VCS.65469.suppl3

Supplementary material 4
Key to the low/tall willow and tussock tundra plant associations from the Ecological Land Survey Legacy Database (ELD) Arctic Plant Association Classification, Alaska. PDF
Link: https://doi.org/10.3897/VCS.65469.suppl4

Supplementary material 5
Descriptions of preliminary (n = 4–9) and provisional (n ≥ 10) low/tall willow and tussock tundra plant associations from the Ecological Land Survey Legacy Database (ELD) Arctic Plant Association Classification, Alaska. PDF
Link: https://doi.org/10.3897/VCS.65469.suppl5

Supplementary material 6
Cross-reference between low/tall willow and tussock tundra preliminary (n = 4–9) and provisional (n ≥ 10) Plant Associations and plant community types (n < 4) from the Ecological Land Survey Legacy Database (ELD) Arctic Plant Association Classification and existing classifications from the literature for Alaska. PDF
Link: https://doi.org/10.3897/VCS.65469.suppl6

Supplementary material 7
Toposequence diagram illustrating the landscape relationships for a river bar to inland dune sequence, North Slope, Alaska. PDF
Link: https://doi.org/10.3897/VCS.65469.suppl7